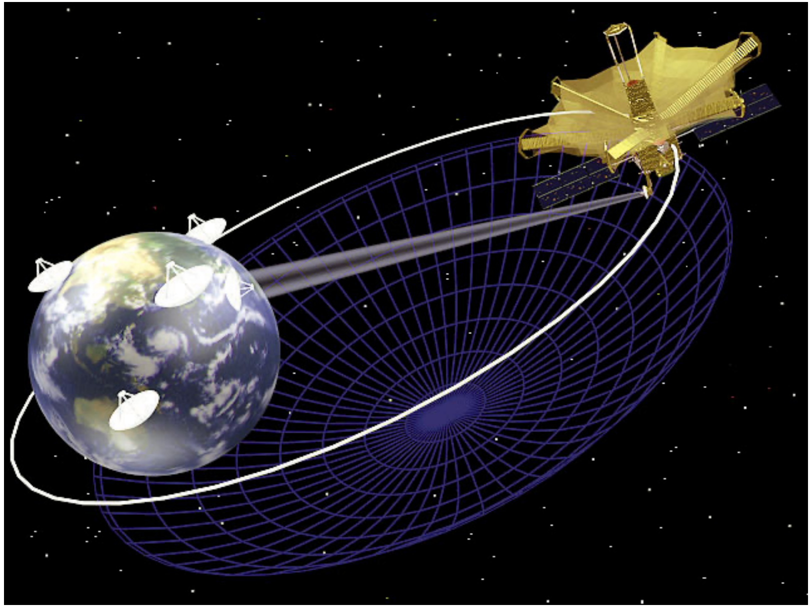
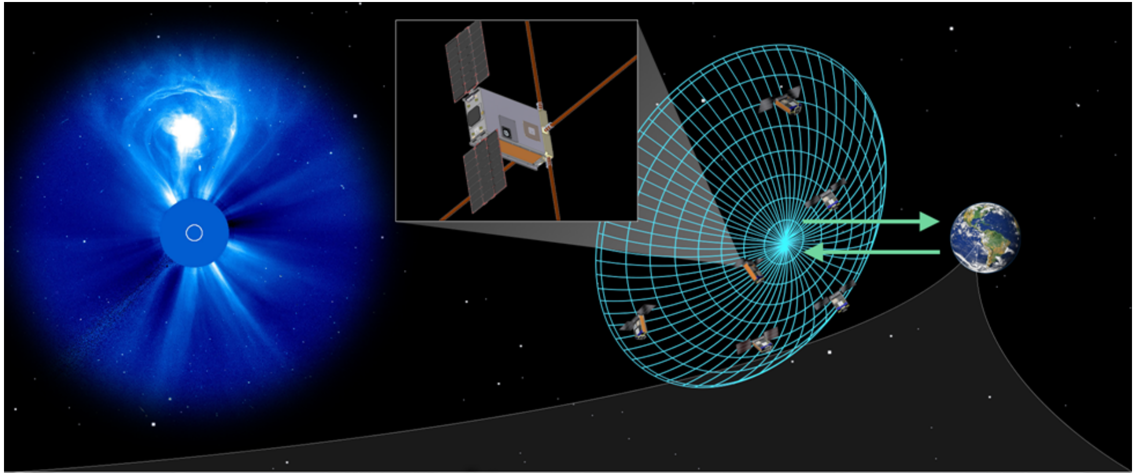




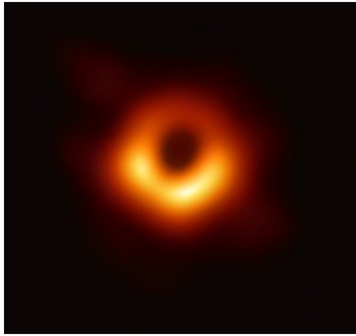
Black Hole PIRE Webinar

Space Interferometry

Joseph Lazio

Jet Propulsion Laboratory
California Institute of Technology

Overview



Credit: Event Horizon Telescope collaboration et al.

Overview

- Introduction and Historical Background
- Interfere-o-what?
- Science Motivations and Potential Missions

Objectives and Outcomes

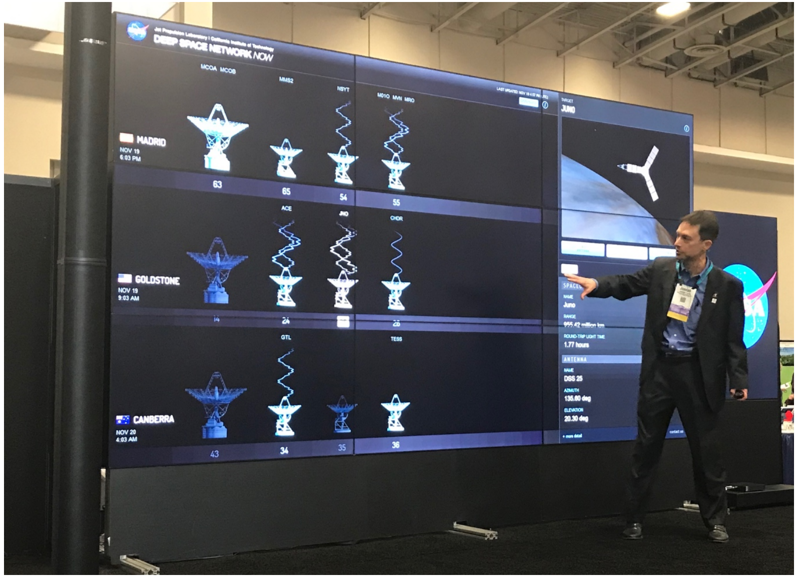
- Heuristic understanding of interferometry
  - a.k.a. possible to construct large synthetic telescopes by combining small ones in appropriate manner
- Appreciation for science motivations and rationale for potential future space missions
- Understanding that astronomy is conducted at many different wavelengths (colors of light) and that different wavelengths provide different information about the Universe

Aside

Joseph Lazio

Who?

- **Chief Scientist, NASA’s Deep Space Network**
- **Boy who always wanted to grow up to be radio astronomer**
- **Involved in early development of Low Frequency Array (LOFAR) and Long Wavelength Array (LWA)**
- **Former Project Scientist for Square Kilometre Array (SKA)**
- **Involved in multiple lunar radio telescope concepts**
- **Project Scientist for space-based interferometer under consideration by NASA**

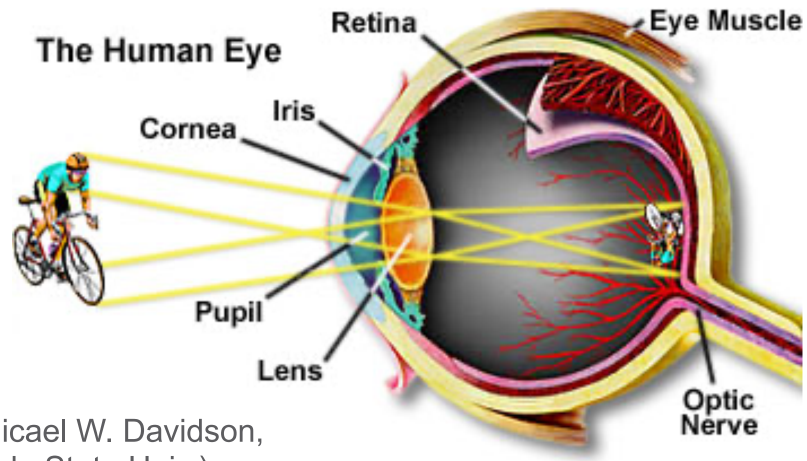


Historical Background

Pre-20th Century

Human eye capable of diffraction-limited imaging of about 1 arcminute

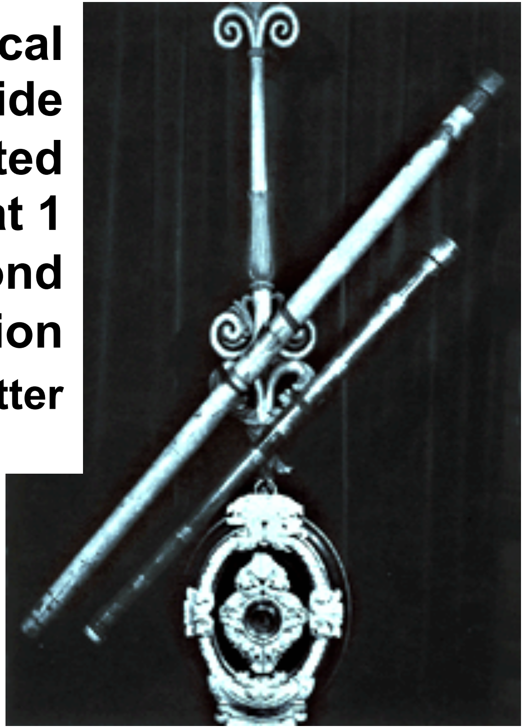
- **20/20 vision ~ U.S. quarter across football pitch**



Credit: Micael W. Davidson, (Florida State Univ.)

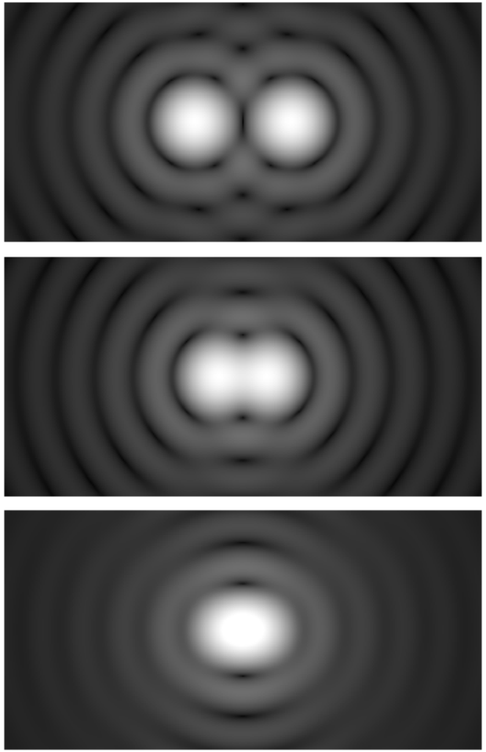
Modest optical telescopes provide diffraction-limited imaging at 1 arcsecond resolution

- **60× better**



Angular Resolution and Optics

Can Two Stars Be Split?



Credit:
Spencer Bliven

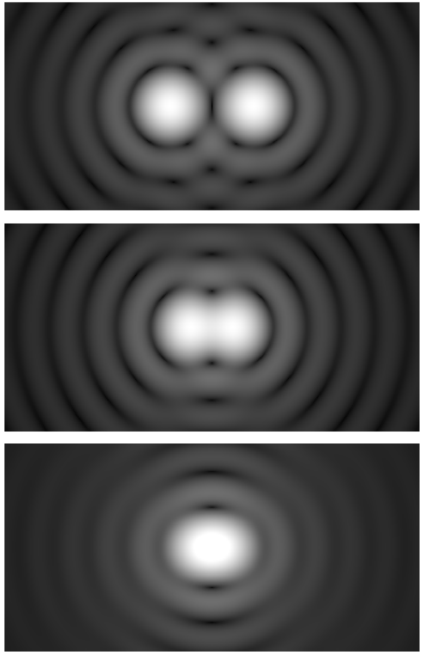
Fundamental optics

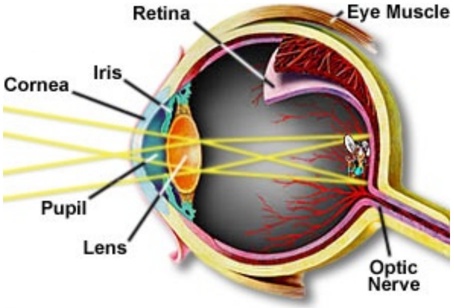
$$\theta = \lambda/D$$

- **λ = observing wavelength**
- **D = diameter of aperture**

Angular Resolution and Optics

Human Eye



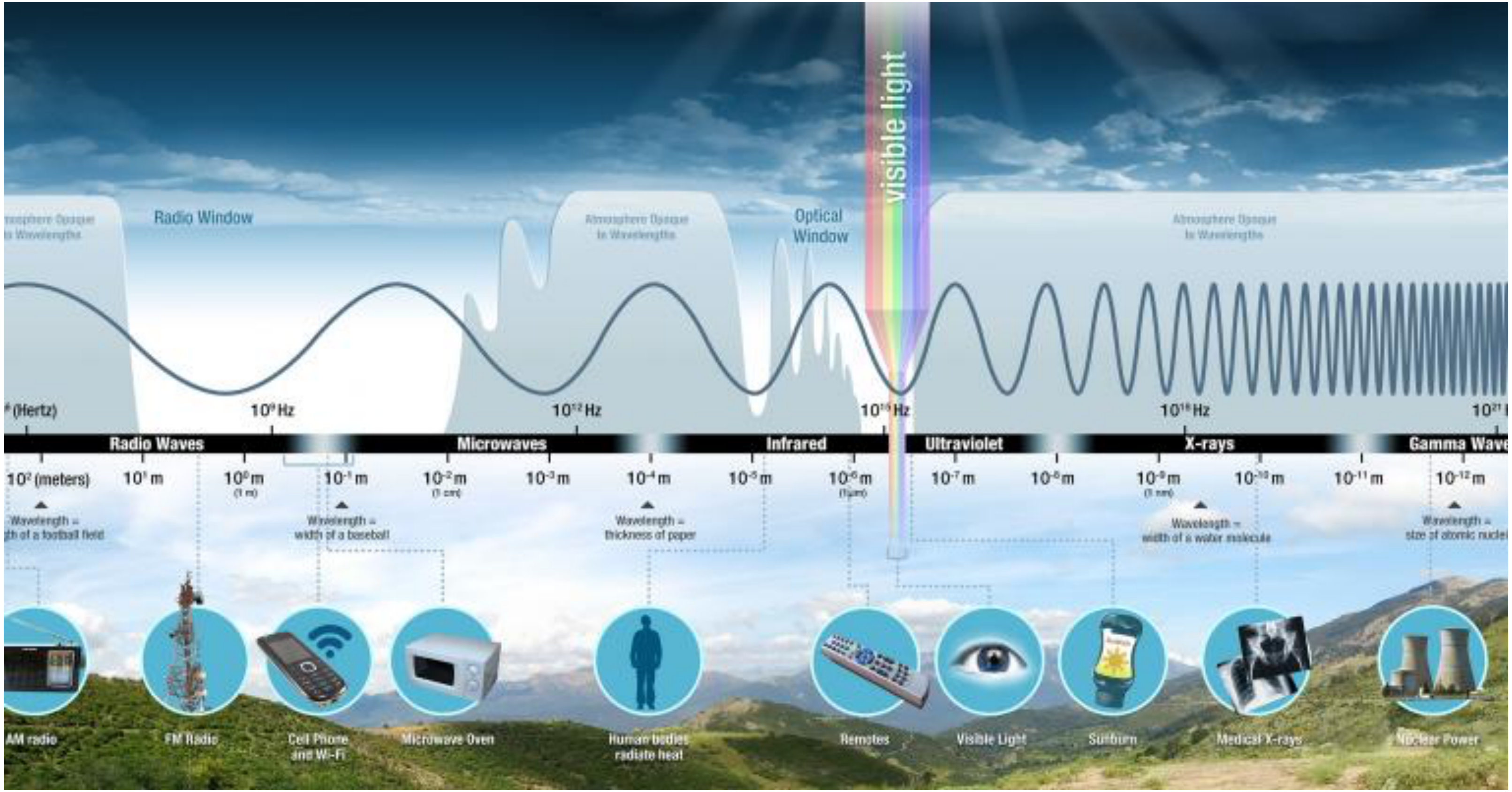


- λ ~ 550 nm (~ 0.00055 mm)
  - observing wavelength
  - green-yellow light
- D ~ 5 mm
  - diameter of pupil (aperture)

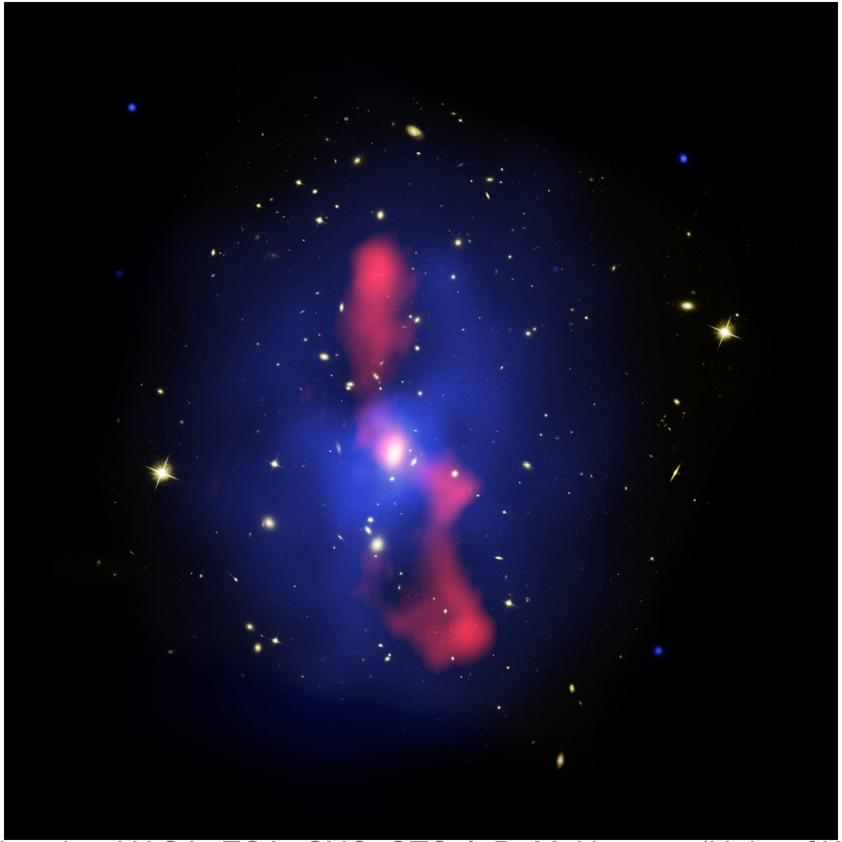
✓ θ ~ 0.00011 radians ~ 0.0063° ~ 0.4 arcminutes

$$\theta = \lambda/D$$

Electromagnetic Spectrum



Full View of the Universe



Credit:
Hubble and Chandra: NASA, ESA, CXC, STScI, B. McNamara (Univ. of Waterloo)
Very Large Array: NRAO, L. Birzan and team (Ohio Univ.)

MS 0735.6+7421

- **Cluster of galaxies**
  - **About 2.6 billion light-years away**
  - **In the constellation Camelopardalis**
- **Three views**
  - **Blue: Chandra X-ray Observatory**
  - **White: *Hubble Space Telescope***
  - **Red: Very Large Array**

Interferometry

Angular Resolution and Optics

Radio Telescopes

- λ ~ 0.30 m (~ 1 GHz)
- D ~ 300 m

  diameter of telescope

➢ θ = 0.001 radians ~ 0.06° ~ 3 arcminutes

$$\theta = \lambda/D$$

! Your eye has higher angular resolution than Arecibo telescope!

Angular Resolution and Optics

Radio Telescopes

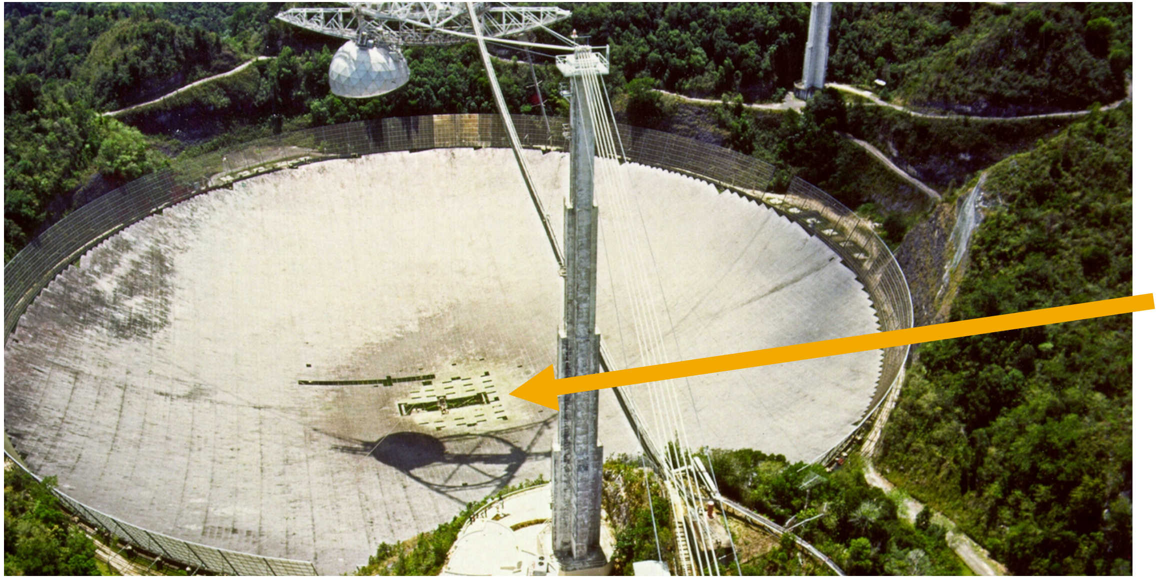
- **Arecibo diameter ~ 300 m**

?? **Match angular resolution of human eye ~ 1 km**

?? **Match angular resolution of modest visible wavelength telescope ~ 10 km**

Angular Resolution and Optics

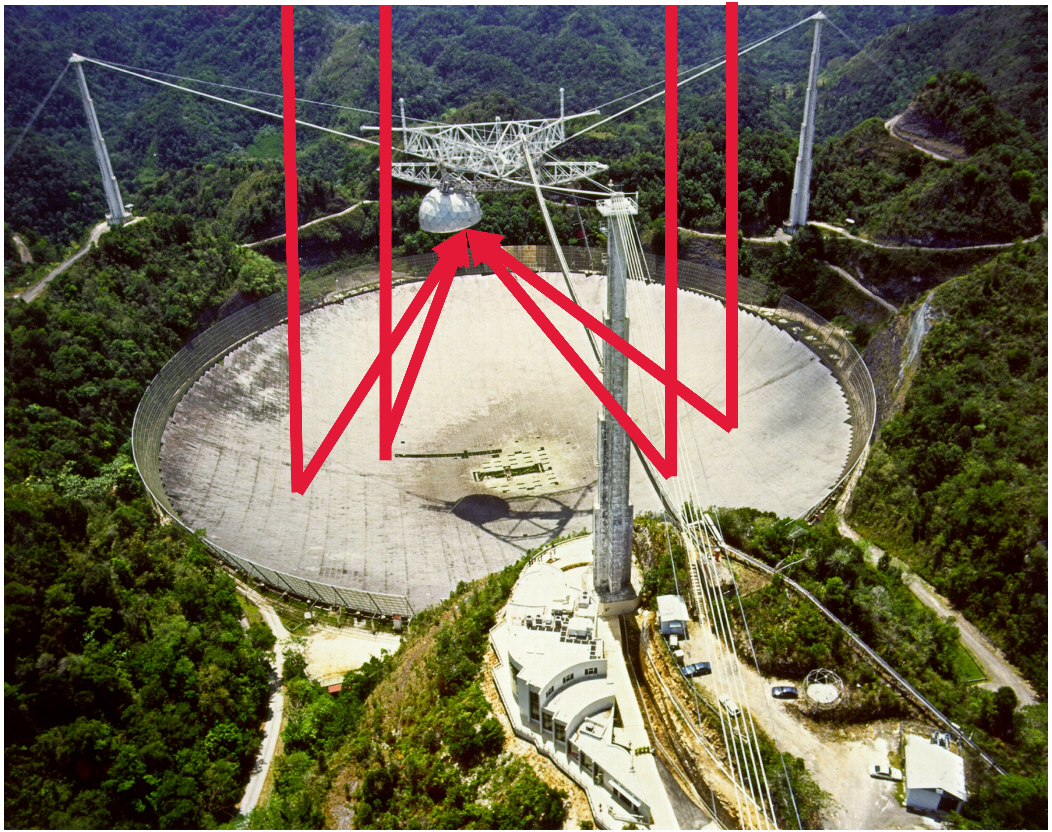
Radio Telescopes



Arecibo has hole in its middle!

How many holes can a telescope have and still work?

How Do Telescopes Work?



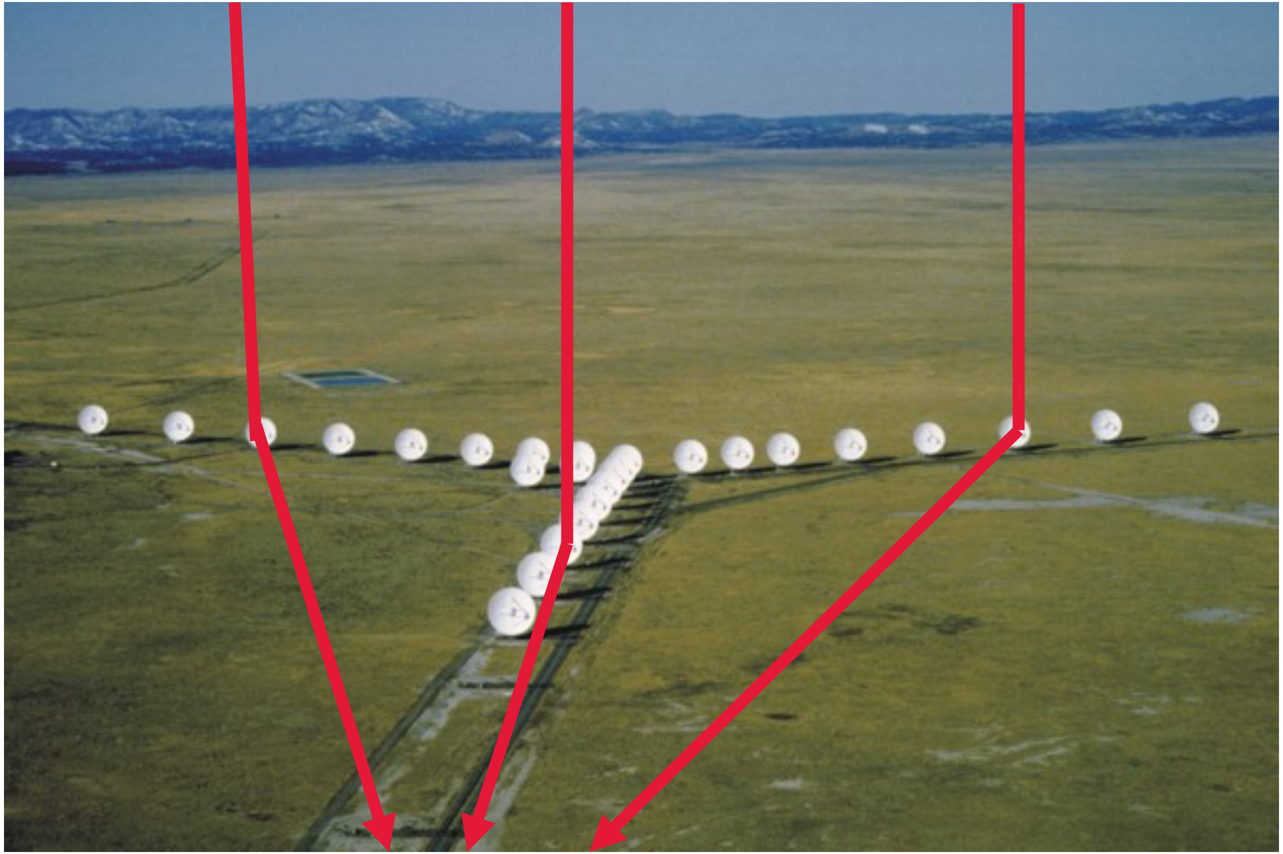
Exercise for the reader:

Consider a parabolic surface.

Show that initially parallel light rays, all traveling at the speed of light *c*, reach a common point, *the focus*, at the same time no matter where they reflect from the surface of the reflector.

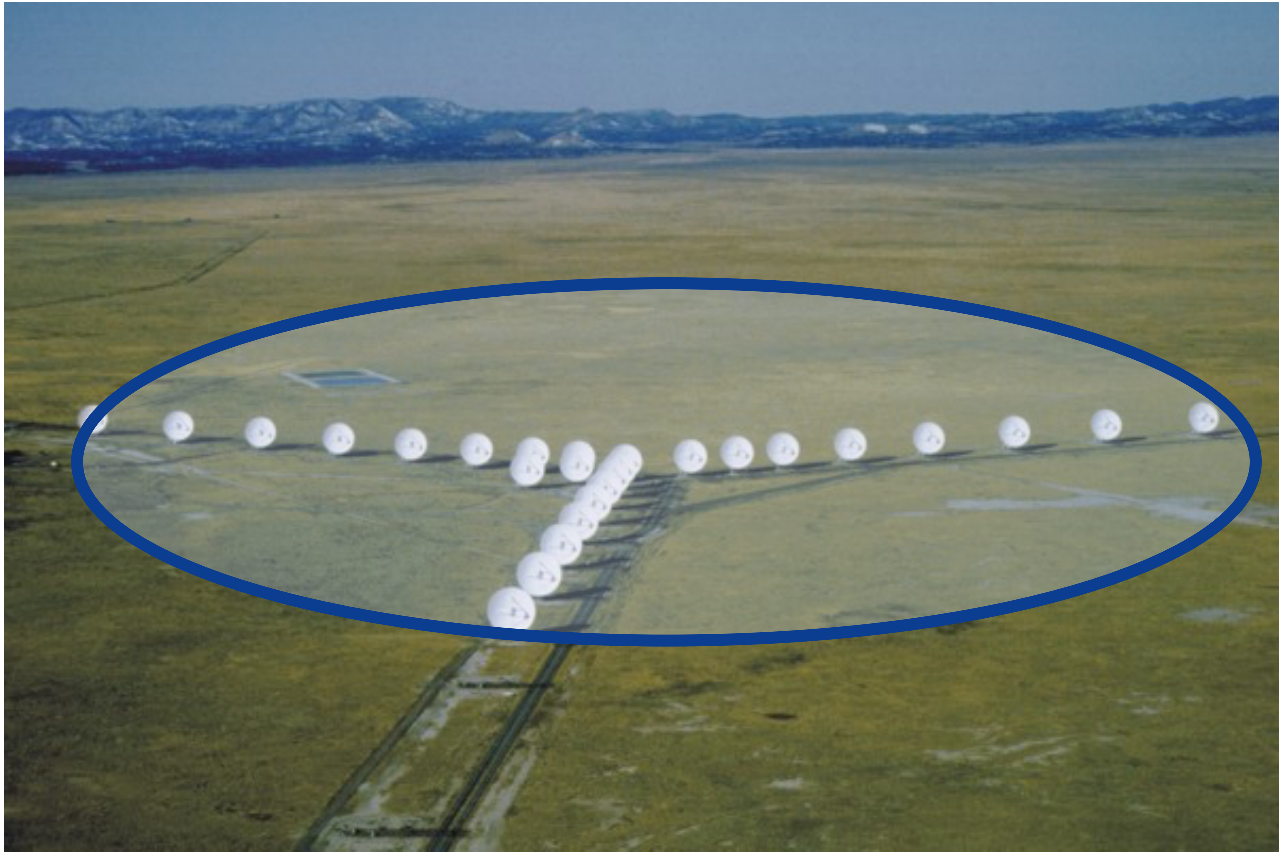
Extra credit: Repeat for a spherical reflector such as Arecibo and show that the focus is a line.

Aperture Synthesis



1. **Record signals at individual antennas**
2. **Bring them together "at the same time" (coherently)**
3. **Then …**

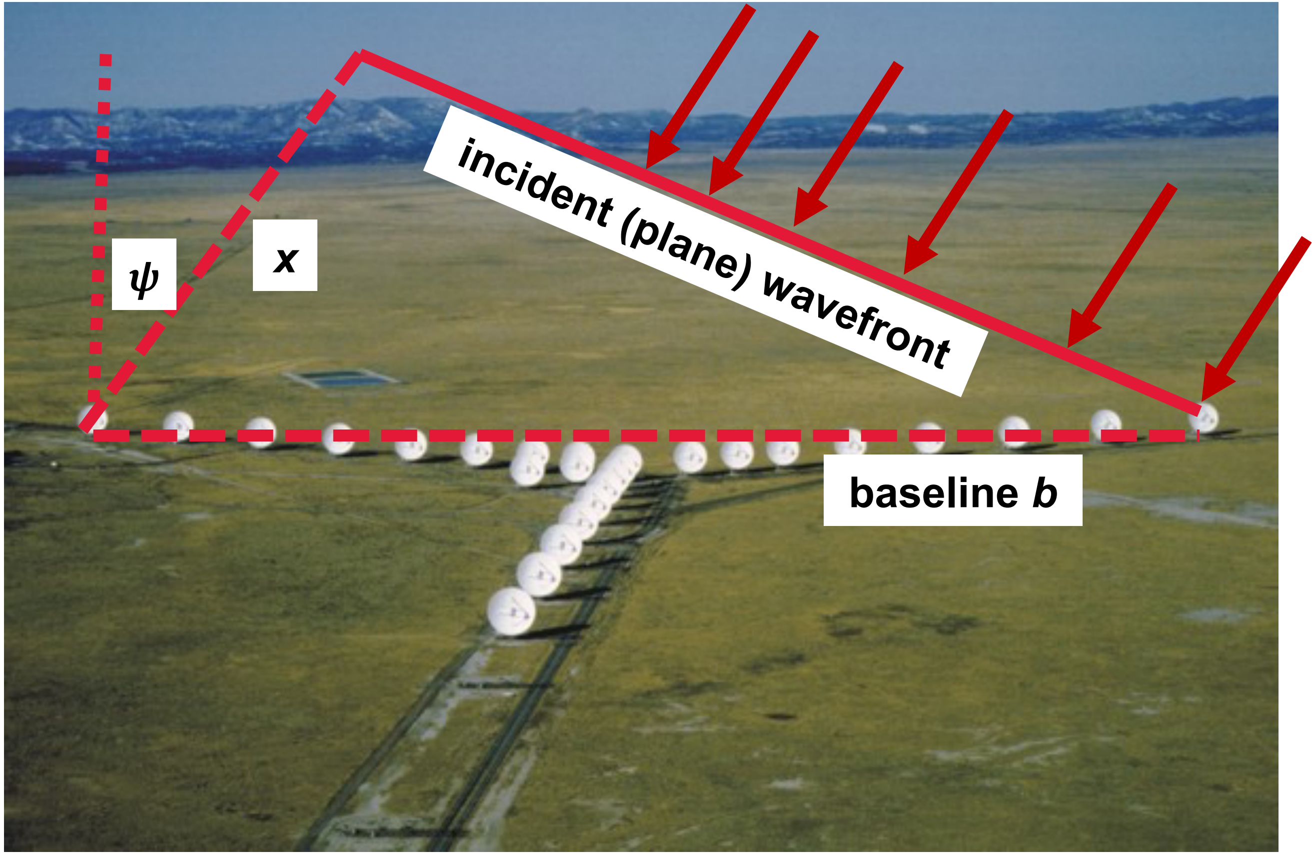
Interferometry or Aperture Synthesis



1. Record signals at individual antennas
2. Bring them together “at the same time” (coherently),
3. Then synthesize aperture!

   a.k.a. build a telescope that’s mostly holes!

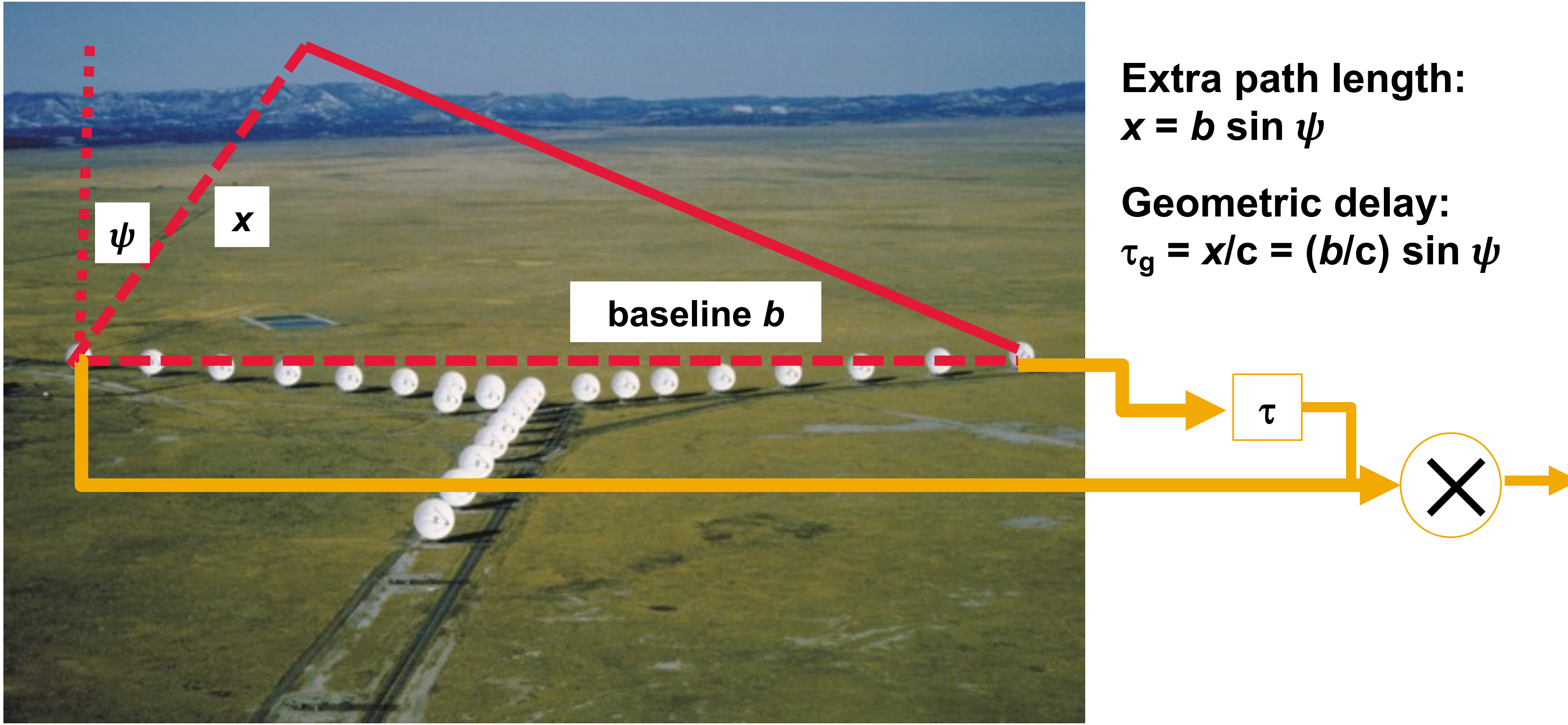
Aperture Synthesis



Extra path length:
$x = b \sin \psi$

Geometric delay:
$\tau_g = x/c = (b/c) \sin\psi$

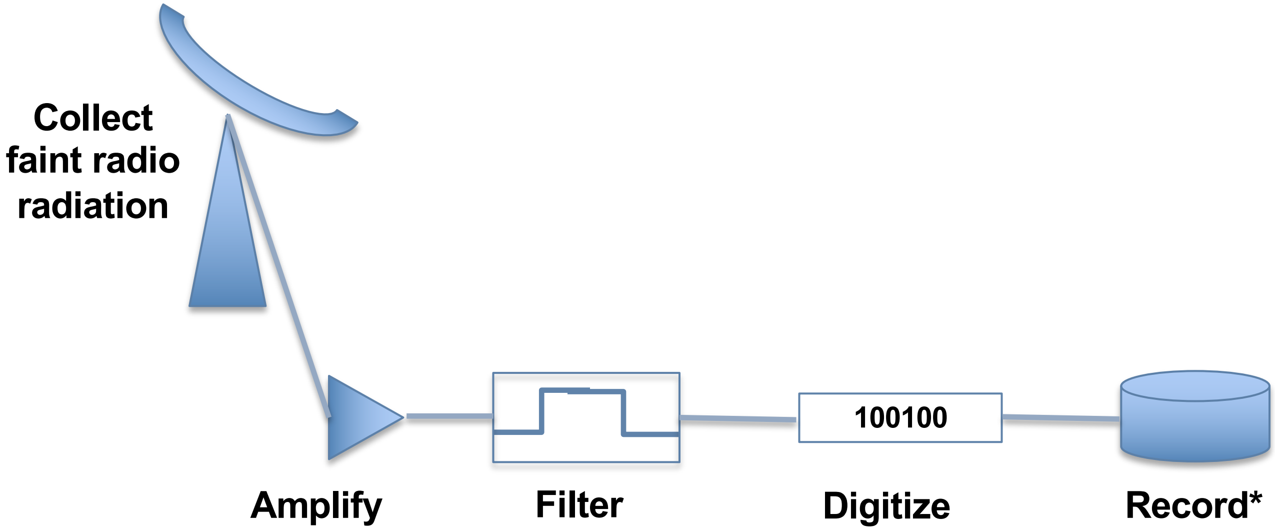
Aperture Synthesis



Extra path length:
$x = b \sin \psi$

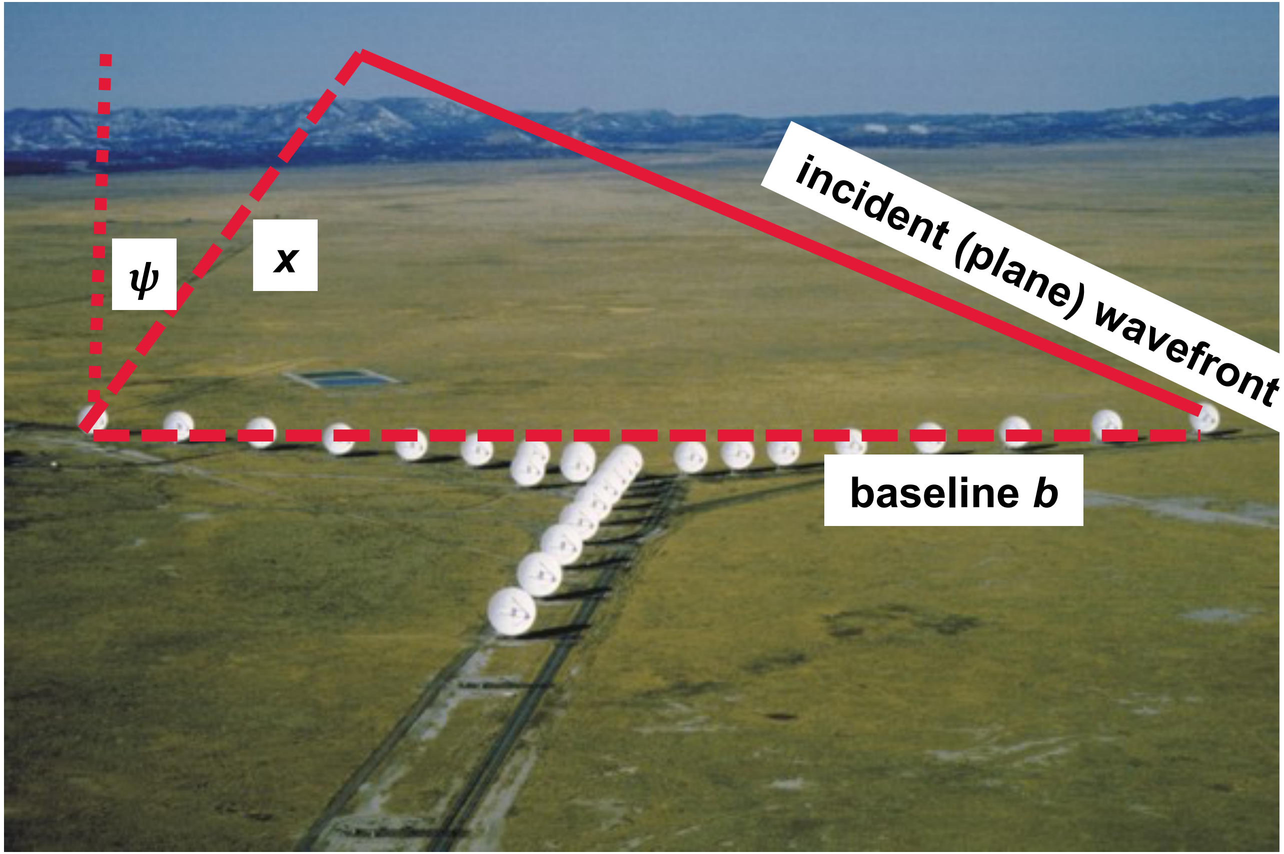
Geometric delay:
$\tau_g = x/c = (b/c) \sin \psi$

Conceptual Radio Telescope



*Today: Record to hard drive disk packs or even direct streaming across the Internet
Historical note: Record on magnetic tapes, including VHS tapes

Aperture Synthesis

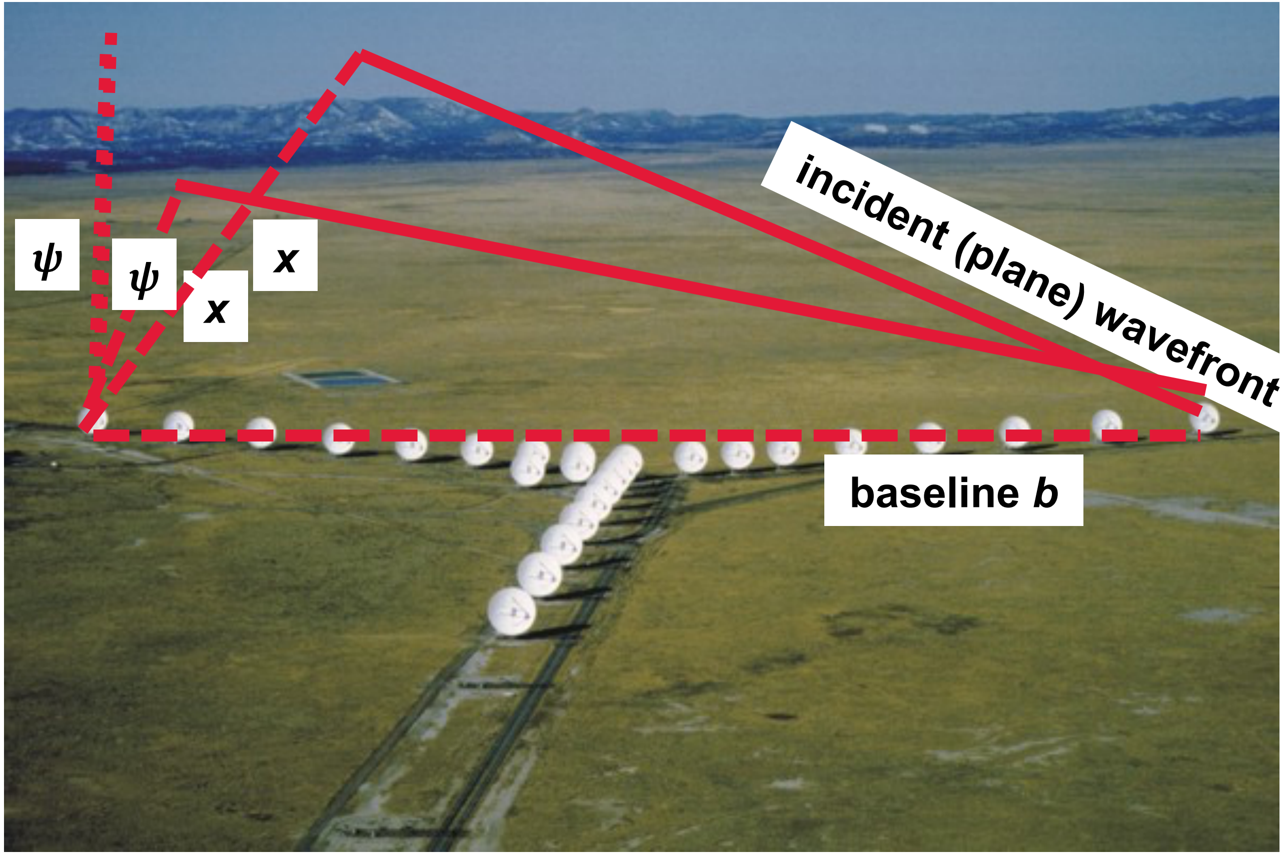


Geometric delay:
$\tau_g = x/c = (b/c) \sin \psi$

Need to know where antennas are

- ***Knowledge*, not control**
- **Only *relative* positions**

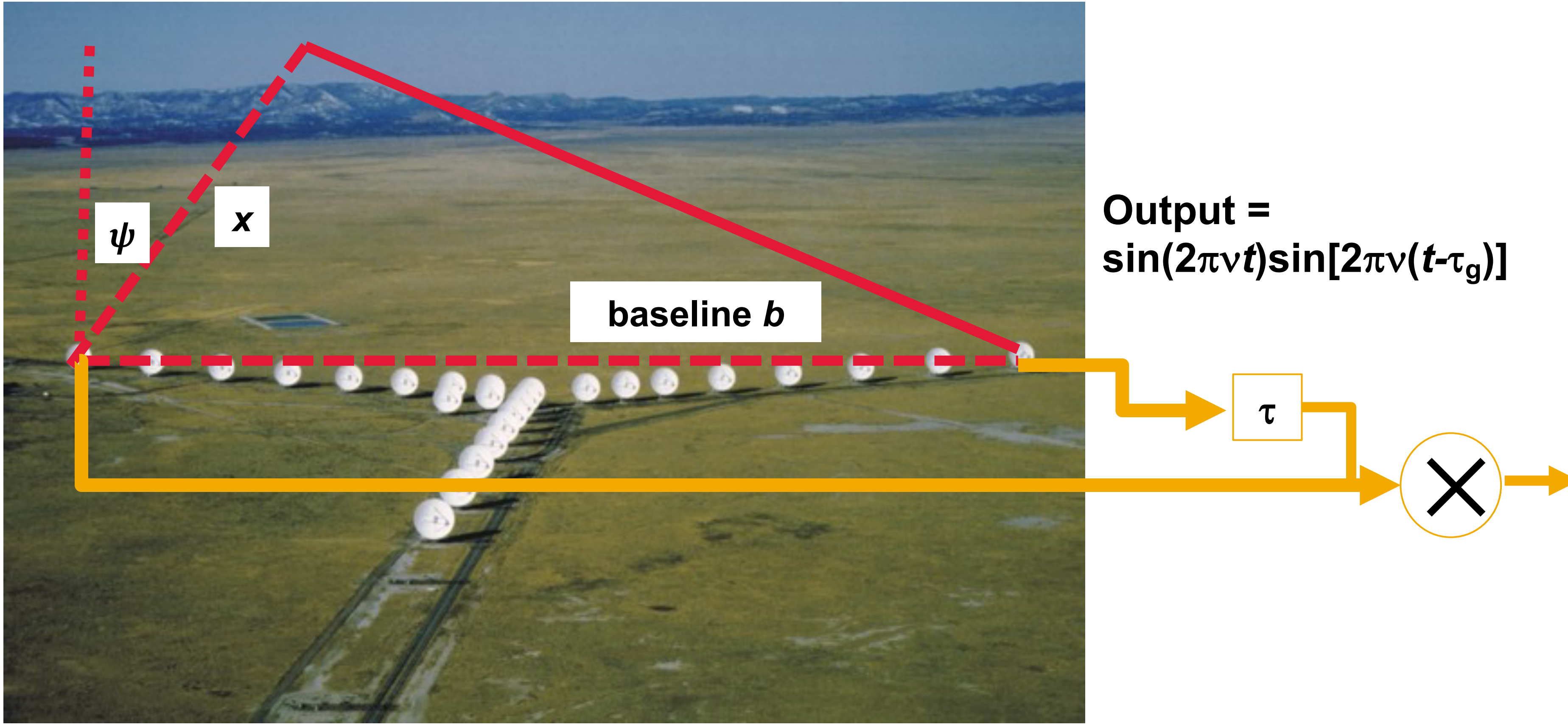
Earth Rotation Synthesis



Geometric delay:
$\tau_g = x/c = (b/c) \sin \psi$

- From perspective of distant observer, array changes shape

Aperture Synthesis Fundamentals



Output =
$\sin(2\pi\nu t)\sin[2\pi\nu(t-\tau_g)]$

Aperture Synthesis Fundamentals

$$\tau_g = (b/c)\sin\psi$$

$$\text{Output} = \sin(2\pi\nu t)\sin[2\pi\nu(t-\tau_g)]$$

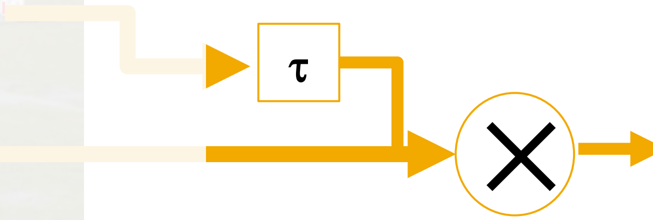
$$\text{Output} = \sin^2(2\pi\nu t)\cos(2\pi\nu\tau_g) - \sin(2\pi\nu t)\cos(2\pi\nu t)\sin(2\pi\nu\tau_g)$$

Average for T >> $1/\nu$ or take $\nu T \gg 1$

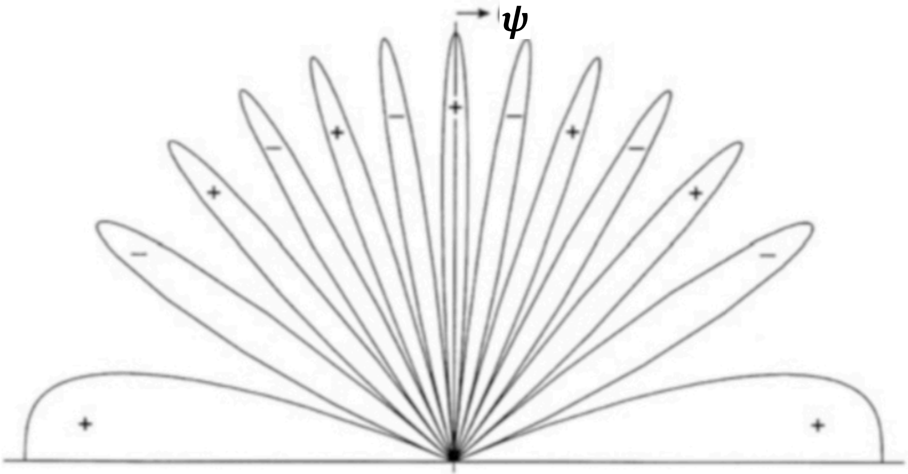
$$\sin^2(\text{big number}) \rightarrow ½$$

$$\sin(\text{big number}) = \cos(\text{big number}) = 0$$

- ➢ $\text{Output} = \cos(2\pi\nu\tau_g)$
- ➢ $\text{Output} = \cos(2\pi[b/\lambda]\sin\psi)$



Aperture Synthesis Fundamentals



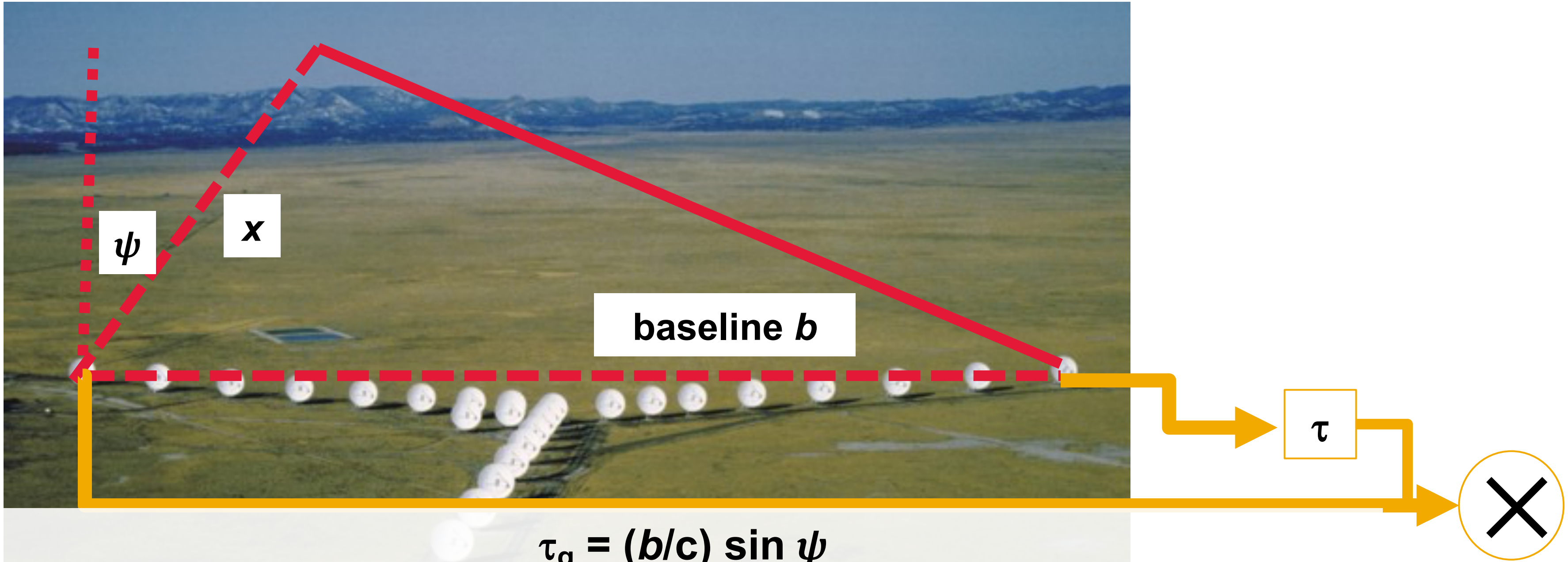
$$\tau_g = (b/c)\sin\psi$$

$$\text{Output} = \sin(2\pi\nu t)\sin[2\pi\nu(t-\tau_g)]$$

- $\text{Output} = \cos(2\pi[b/\lambda]\sin\psi)$

Thompson, Moran, & Swenson

Aperture Synthesis Fundamentals

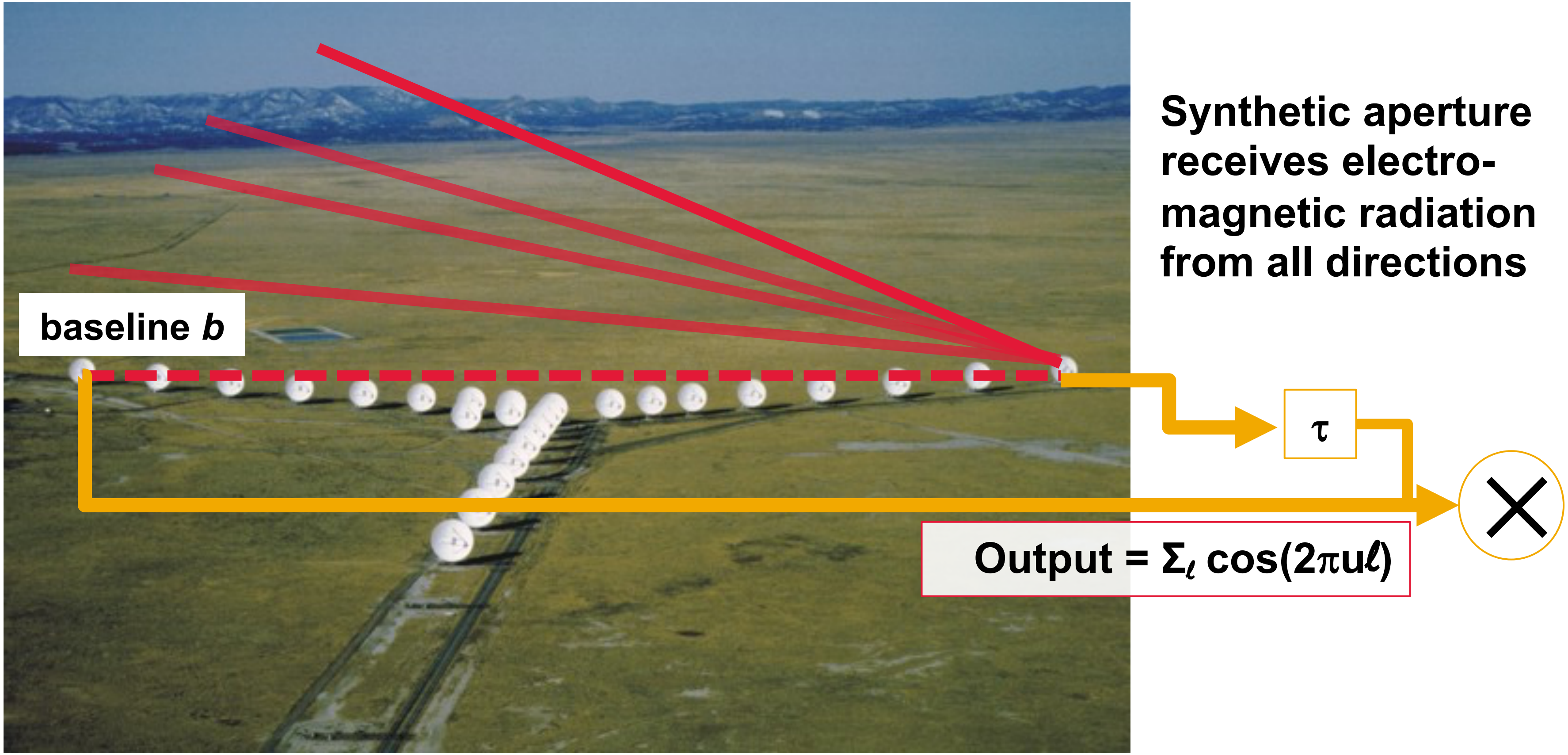


$\tau_g = (b/c) \sin \psi$

➢ Output = $\cos(2\pi[b/\lambda]\sin \psi)$

$u = b/\lambda$ and $\ell = \sin \psi$

Aperture Synthesis Fundamentals



Synthetic aperture receives electro-magnetic radiation from all directions

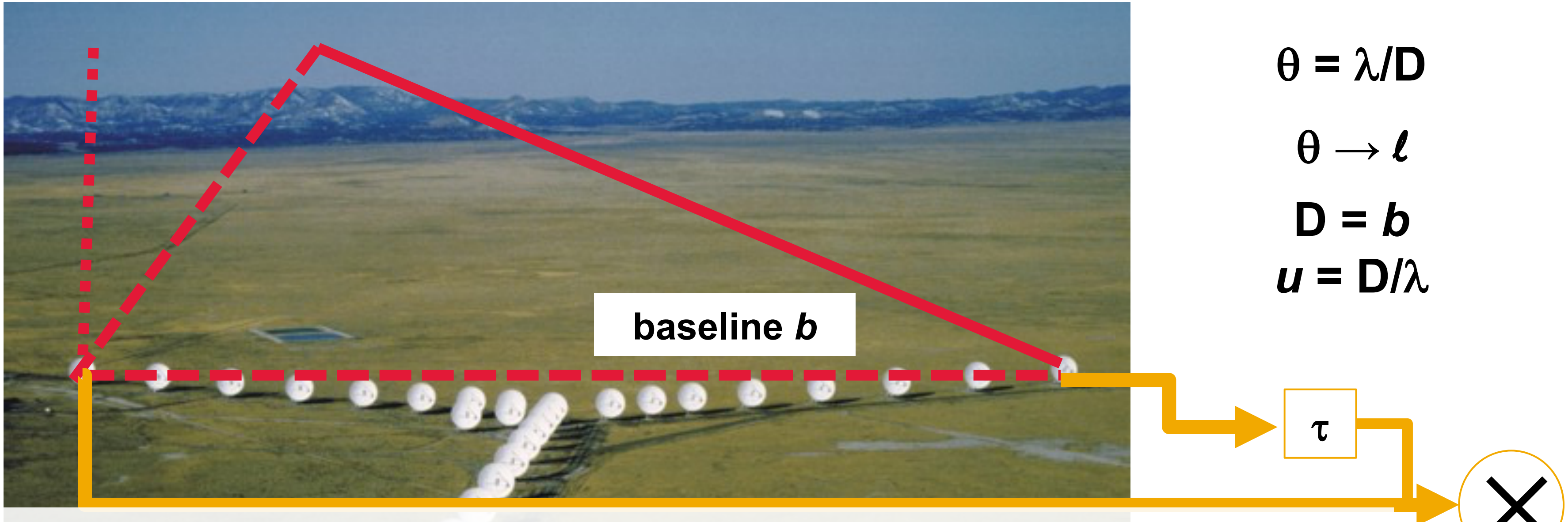
Aperture Synthesis Fundamentals

$\theta = \lambda/D$

$\theta \rightarrow \ell$

$D = b$

$u = D/\lambda$



- **Output = $\Sigma_\ell \cos(2\pi u \ell)$**

$u = b/\lambda$ and ℓ are Fourier conjugates

- **Big u means small ℓ; small u means big ℓ**

Aperture Synthesis Fundamentals

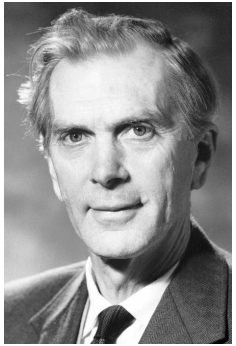
Mid-Term Review

- ✓ **Receptor/antenna separation, measured in wavelengths, is equivalent to aperture diameter.**
  - **True for any optical instrument, not just synthetic apertures**
- ✓ **Baselines (a.k.a. antenna separations) determines angular resolution.**
  - **Distribution of baselines affects performance of synthetic aperture a.k.a. no free lunch theorem.**
- ✓ **Knowledge of relative antenna separations is critical.**

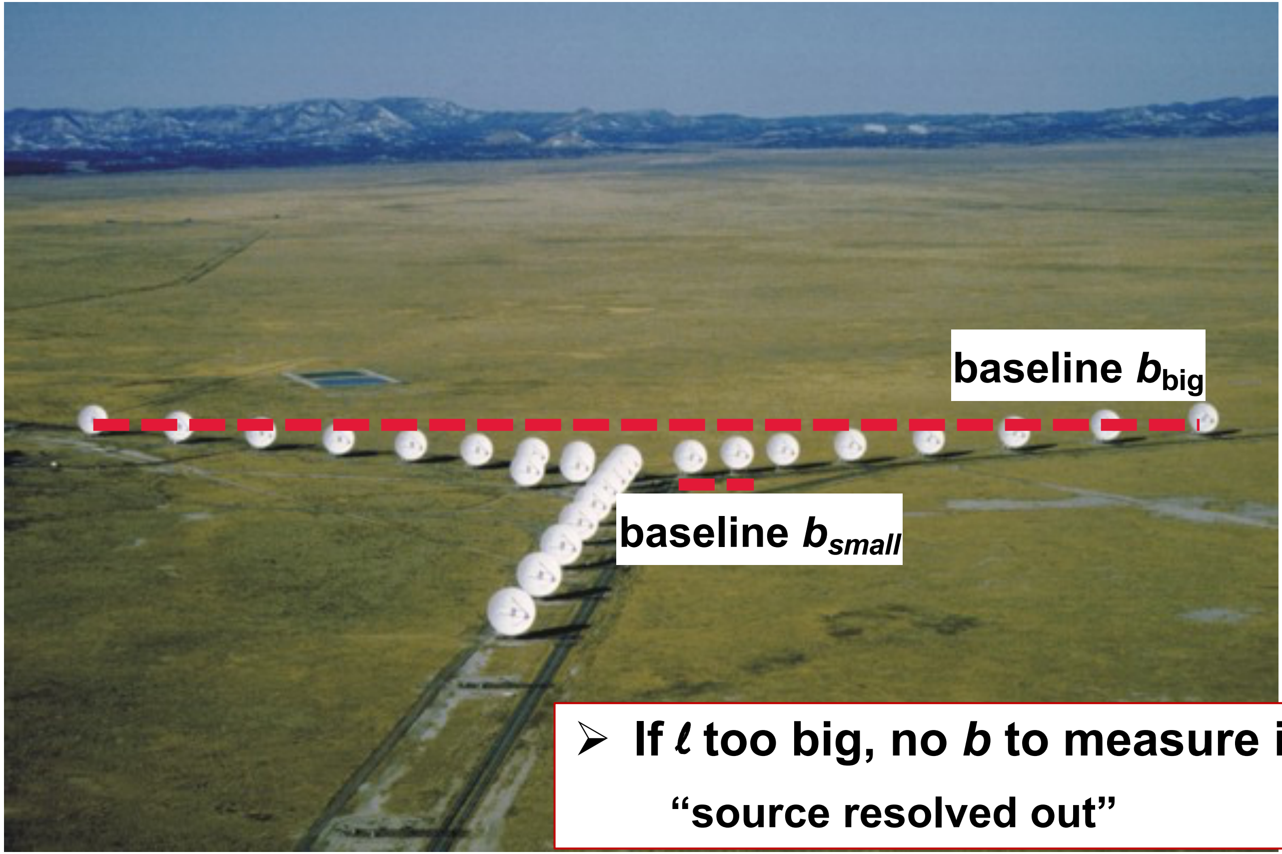
Aperture Synthesis

1974 Nobel Prize in Physics

The Nobel Prize in Physics 1974 was awarded jointly to Sir Martin Ryle and Antony Hewish "for their pioneering research in radio astrophysics: Ryle for his observations and inventions, in particular of the aperture synthesis technique, *and Hewish for his decisive role in the discovery of pulsars.*"



Aperture Synthesis Fundamentals



$\theta = \lambda/D$

✓ Big u (or large b) means small ℓ

- Small u (or small b) means big ℓ

  "largest angular scale"

Whoa!

➤ If ℓ too big, no b to measure it!

"source resolved out"

Van Cittert-Zernike Theorem

Heuristic: Output $= \Sigma_{\ell} \cos(2\pi u \ell)$

$$\Gamma(u,v) = V(u, v) = \int I(\ell, m) e^{-2\pi i(u\ell + vm)}\, d\ell\, dm$$

Van Cittert-Zernike Theorem

Fourier Transform

$$\Gamma(u,v) = V(u,v) = \underbrace{\int I(\ell, m)e^{-2\pi i(u\ell + vm)}\, d\ell\, dm}$$

Sky brightness

Mutual coherence function
a.k.a.
Visibility function

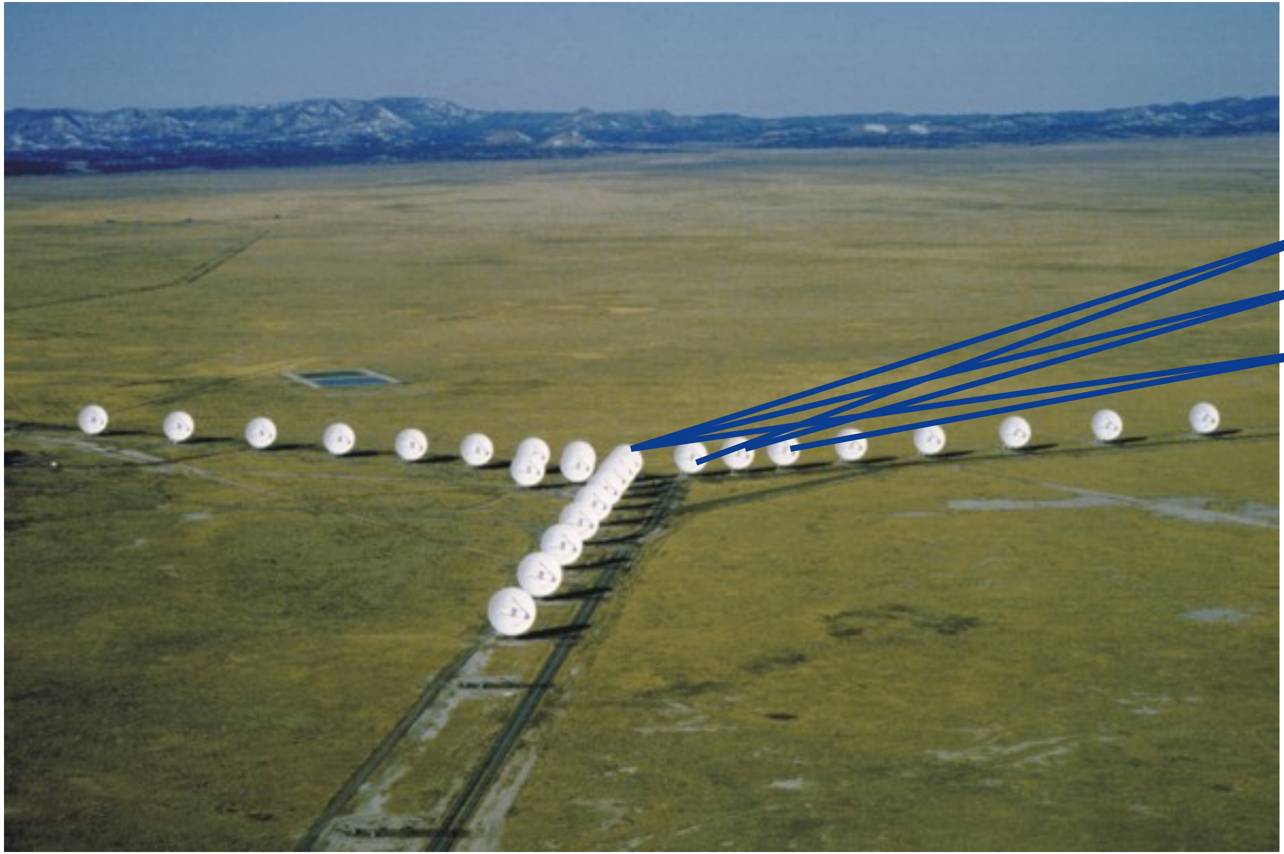
Van Cittert-Zernike Theorem

$$\Gamma(u,v) = V(u, v) = \int I(\ell, m)e^{-2\pi i(u\ell + vm)}\, d\ell\, dm$$

Assumptions

- Narrow field of view
- Co-planar array
- Monochromatic signals (narrow bandwidths)
- Instantaneous signal reception

Aperture Synthesis



$\Gamma_{12}(u, v)$

$\Gamma_{13}(u, v)$

$\Gamma_{14}(u, v)$

.

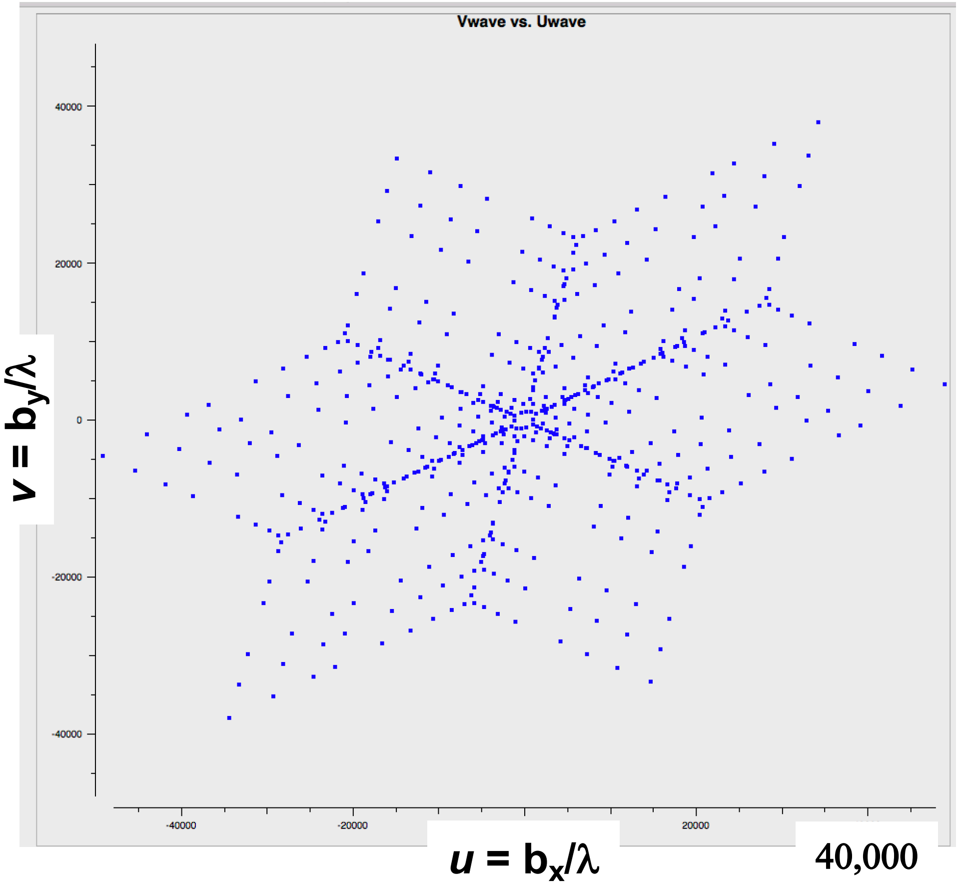
.

.

$\Gamma_{ij}(u, v)$

$$I(\ell, m) = FT[\Gamma(u, v)]$$

Visibilities, *u-v* Plane, (Synthesized) Beams



***u* = 40,000**

b_x = 40,000λ

λ ~ 6 cm (~ 5 GHz)

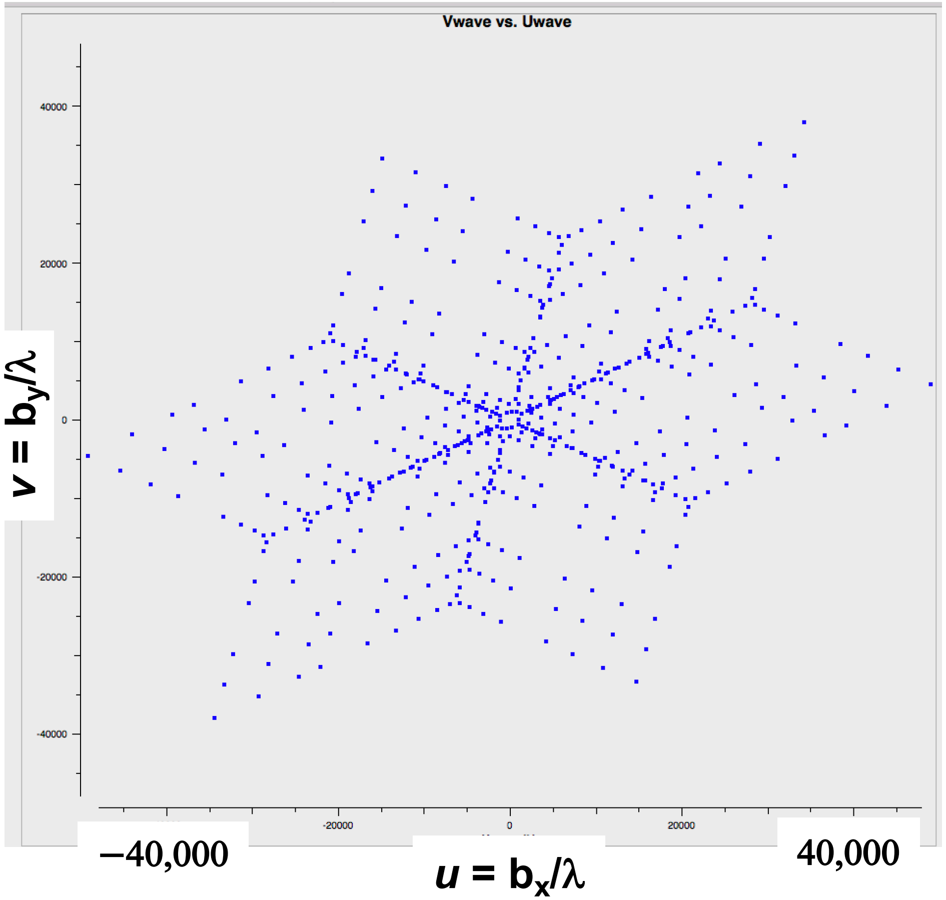
b_x ~ 2.4 km

Aperture is 2.4 km in size!

Resolution ~ 5"

Remember where we started?!

Visibilities, *u*-*v* Plane, (Synthesized) Beams

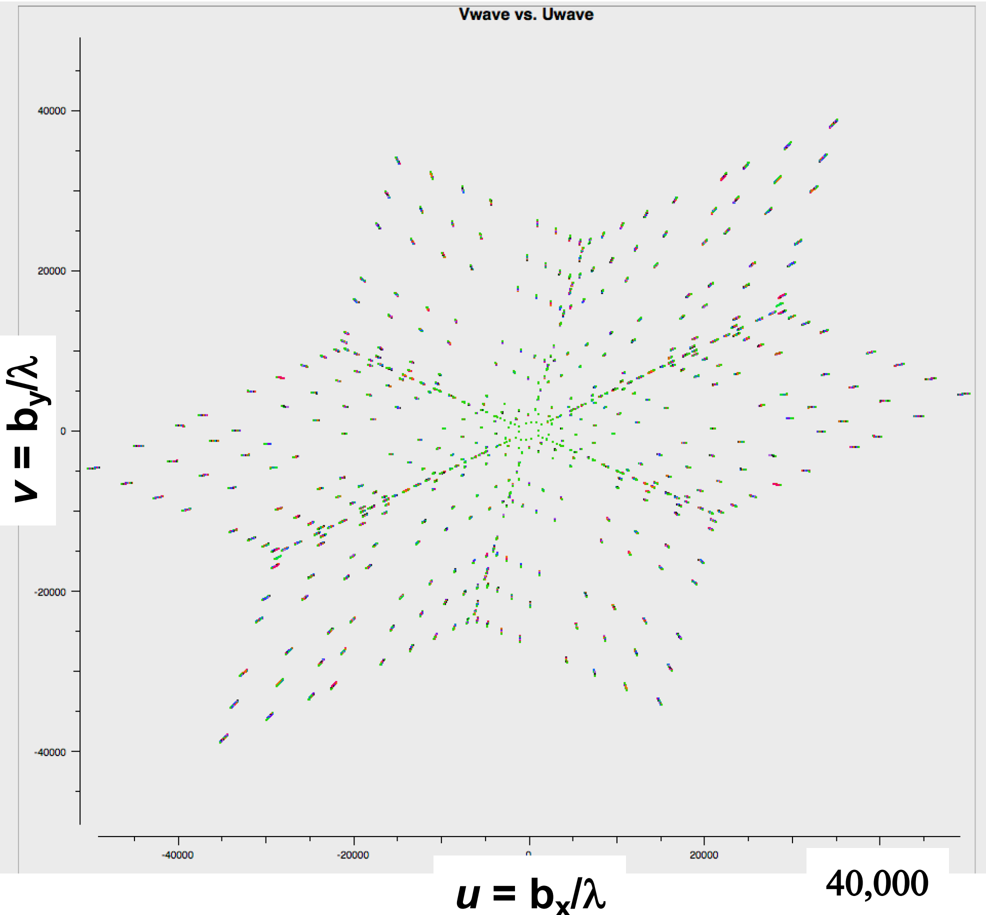


$I(\ell, m) = \mathrm{FT}[\Gamma(u, v)]$

Sky brightness I(ℓ, m) is real quantity

$\Gamma(u, v) = \Gamma^*(u, v) = \Gamma(-u, -v)$

Visibilities, *u-v* Plane, (Synthesized) Beams

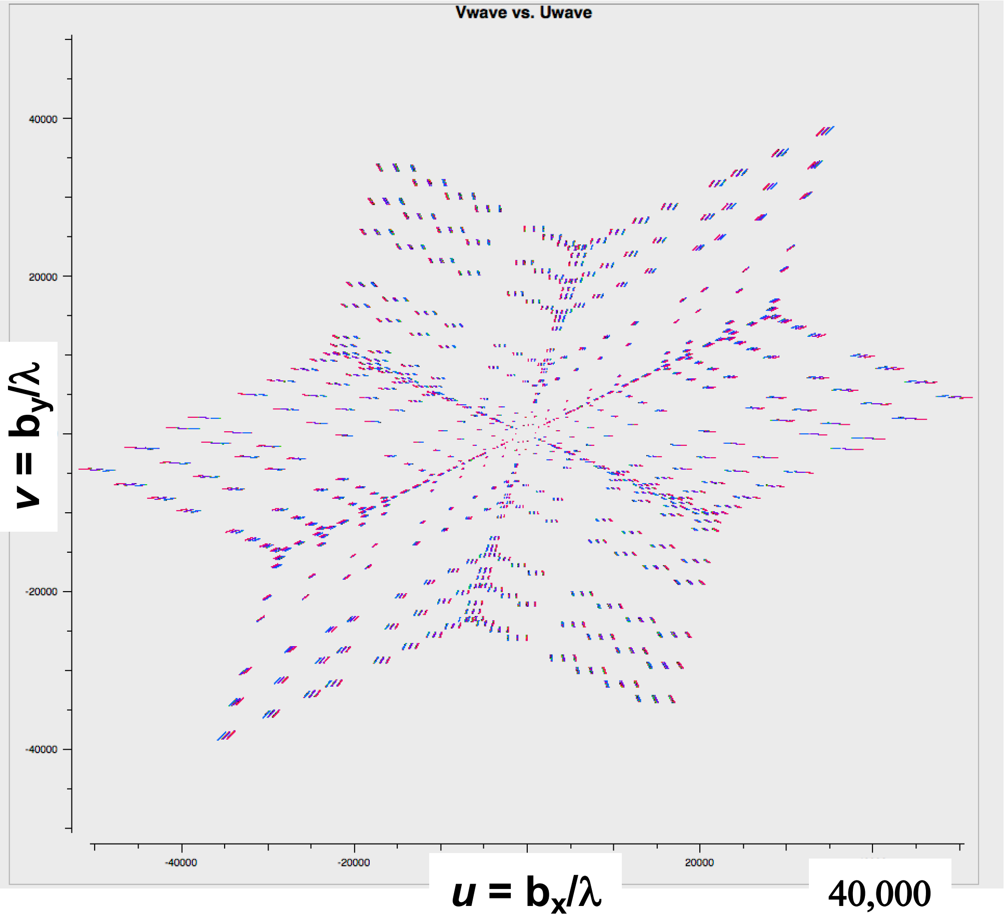


$u = b_x/\lambda$

Sample range of λ or ν, get range of (u, v)

- **Fill in synthetic aperture**

Visibilities, *u*-*v* Plane, (Synthesized) Beams



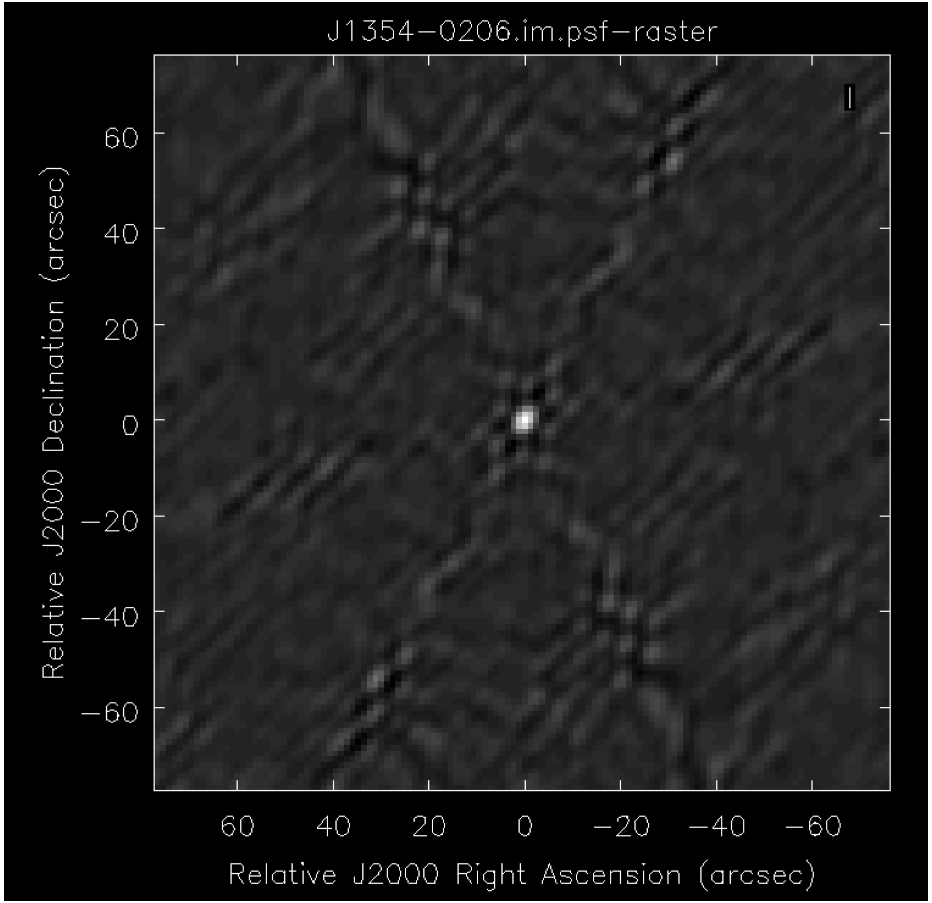
$u = b_x/\lambda$

Baselines change as Earth rotates, $b = b(t)$

Sample over range of time, get range of (u, v)

- **Fill in synthetic aperture**

Visibilities, *u*-*v* Plane, (Synthesized) Beams



$\Pi(u, v) = 1$ if measured
$\Pi(u, v) = 0$ if not measured

Beam = $\mathrm{FT}[\Pi(u, v)]$

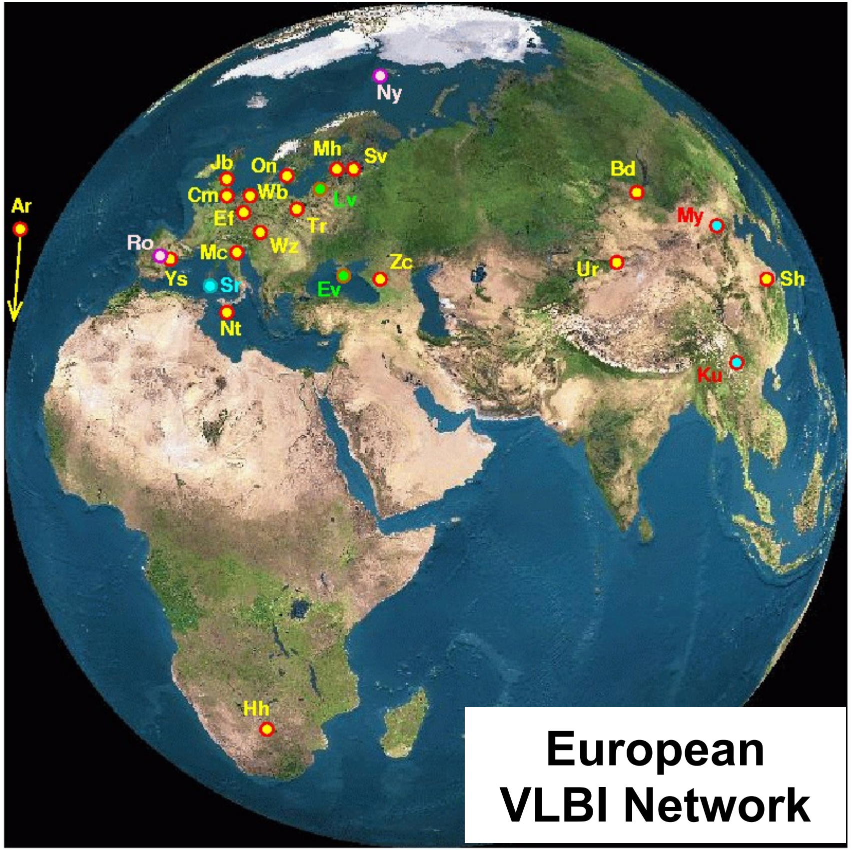
a.k.a. point spread function

Sidelobes!

Measure of performance of telescope

Very Long Baseline Interferometry

Very Long Baseline Array

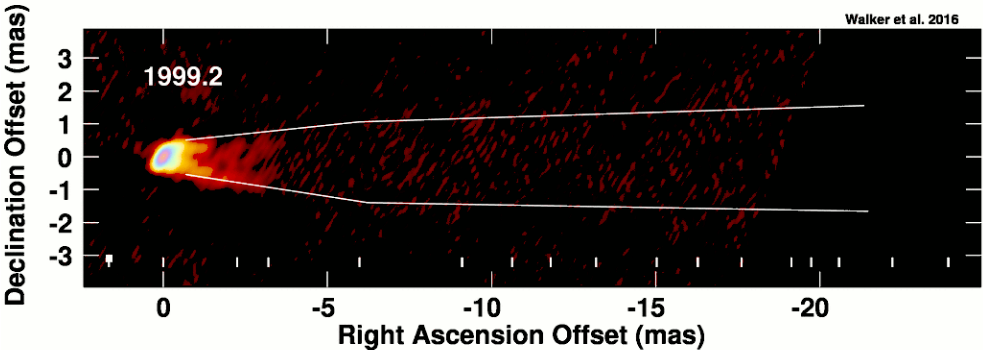


European VLBI Network

Space-based Interferometry

How Small Can Radio Sources Be?

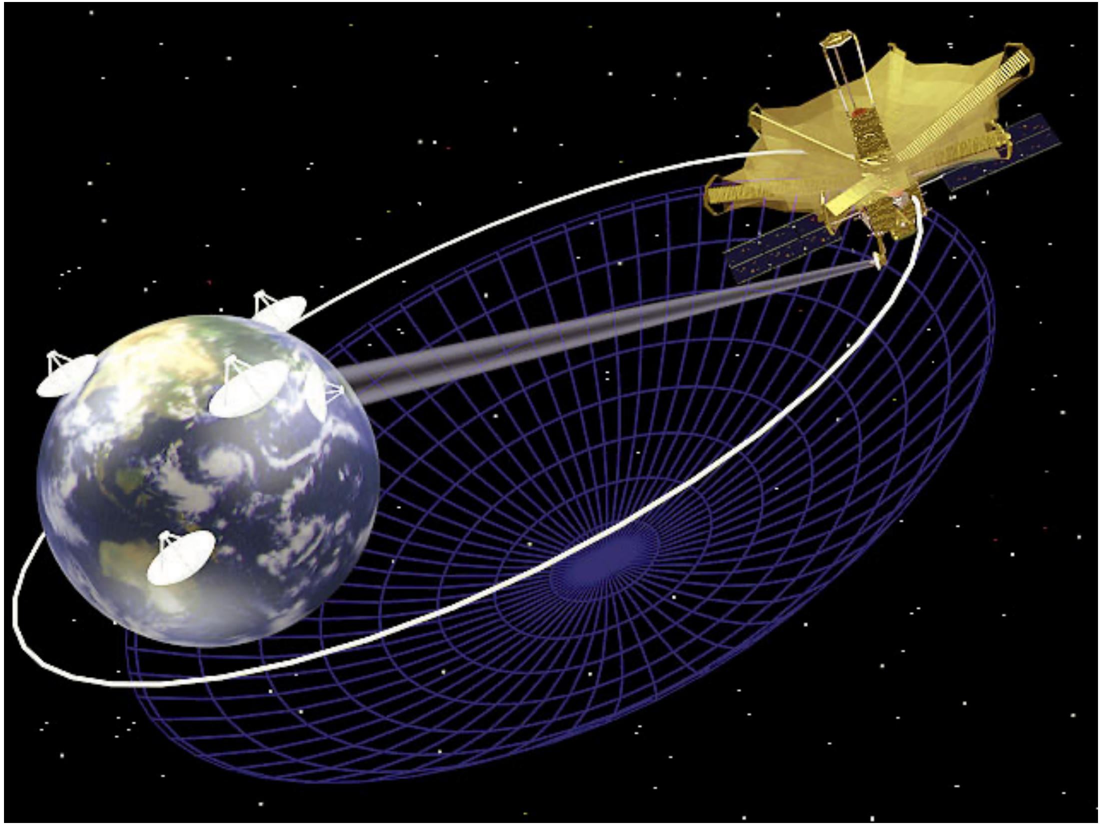
Space-based Interferometry



- **By mid-1970s, clear that some radio sources still unresolved on terrestrial baselines**
- **Also superluminal motion apparent**
- **Heuristically, if source too small, energy density not enough to be visible to terrestrial radio interferometers?**
  - **A.k.a. no free lunch theorem**

    As synthetic apertures, interferometers limited to observing bright sources, because telescope with lots of holes
  - **Inverse Compton catastrophe**

VLBI Space Observatory Program (VSOP) / HALCA



JAXA-led
8 m-diameter space-based antenna

- Some sources still have point-like or unresolved components, implies physics about central engines
    - Coherent or Doppler-beamed emitters

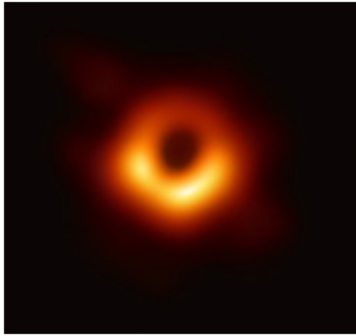
RadioAstron

Roscosmos-led 10 m-diameter space-based antenna

- Baselines comparable to Earth-Moon distance

Black Hole Event Horizon Imaging

Space-based Interferometry



- **In Einstein's General Relativity, black hole is volume disconnected from rest of Universe**
- **Event horizon is boundary between inside black hole and rest of Universe**

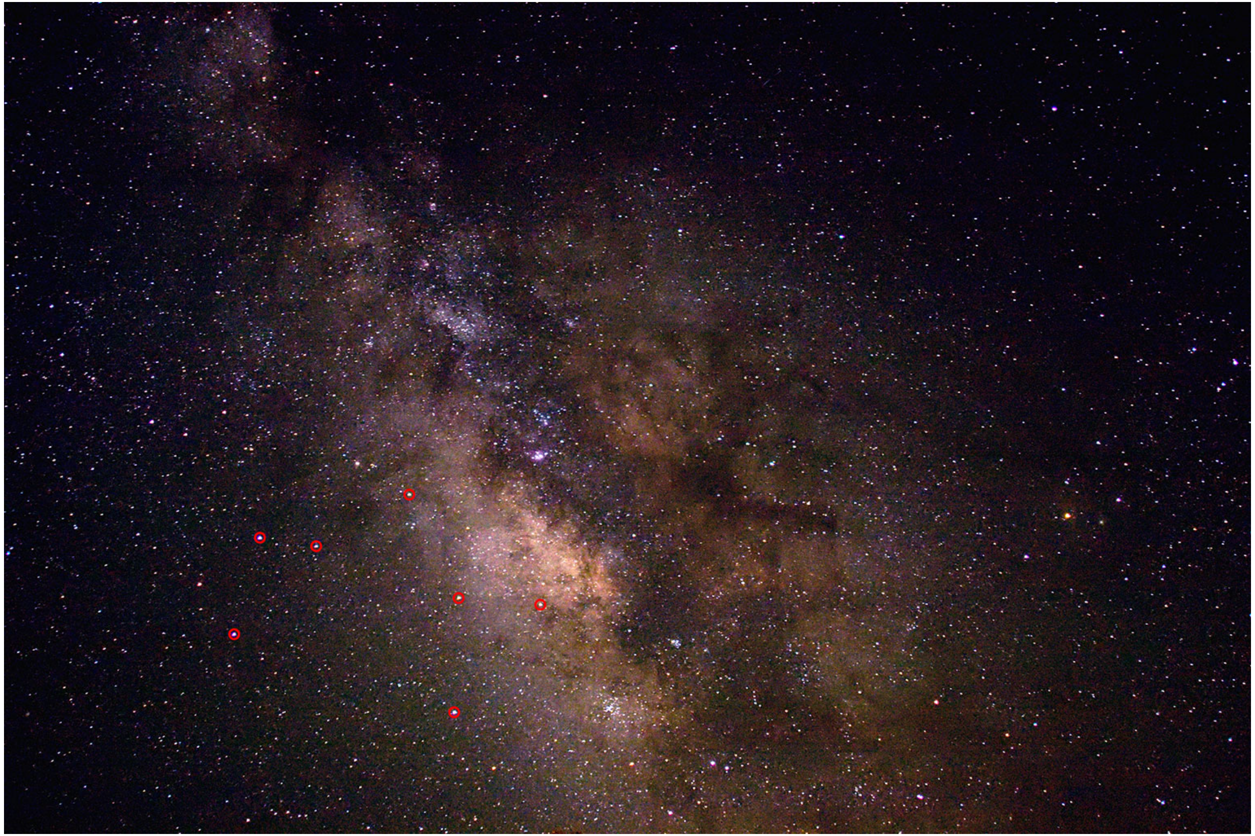
  Schwarzchild radius

  For Sun, $R_s \cong 3$ km

$$R_g = R_s \equiv \frac{2GM}{c^2}$$

Credit: Event Horizon Telescope collaboration et al.

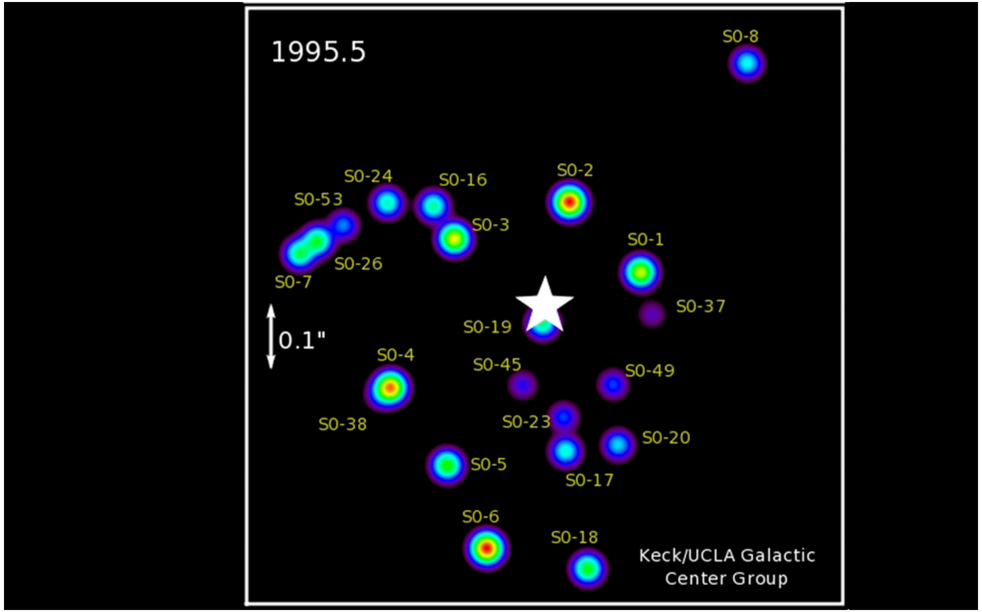
Black Hole Event Horizon Imaging



Credit: Moondigger

Black Hole Event Horizon Imaging

Space-based Interferometry



$$M \sim 4 \times 10^6\ M_\odot$$

$$2R_g/D_{GC} = \sin \ell \sim \ell$$

- $R_g \sim 12 \times 10^6$ km
- $D_{GC} \sim 8000$ pc ($\sim 2.5 \times 10^{17}$ km $\sim$ 26,000 light years)
  - $\ell \sim 9.7 \times 10^{-11}$ radians $\sim$ 20 microarcseconds

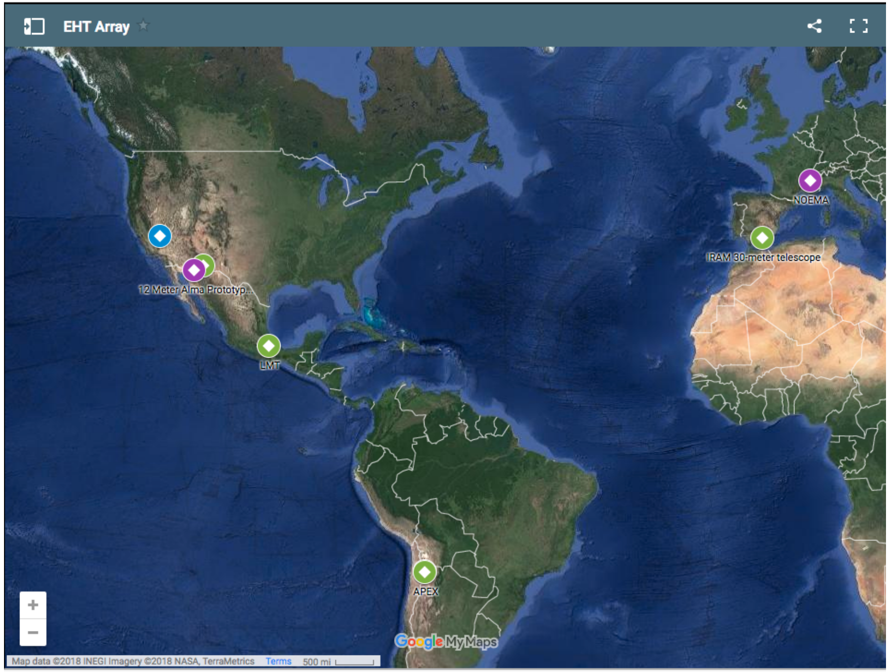
UCLA Galactic Center Group
W.M. Keck Observatory Laser Team

Black Hole Event Horizon Imaging

Space-based Interferometry

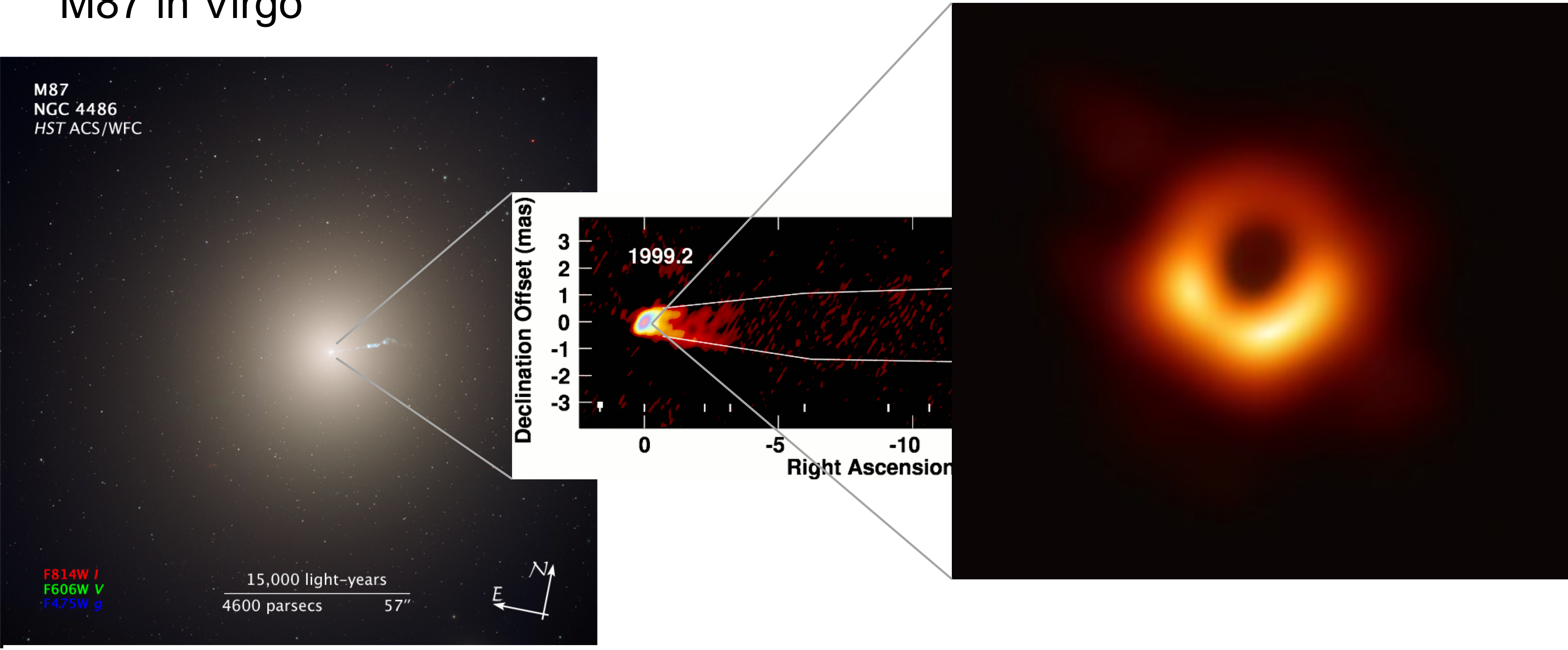
Need ~ 10 microarcsecond resolution

- **Choose λ ~ 0.13 cm**
- **b ~ 10,000 km**
- **Event Horizon Telescope = Earth-scale telescope to image nearby black hole event horizons**
  - **See April 10 press release**



Black Hole Event Horizon Imaging

M87 in Virgo

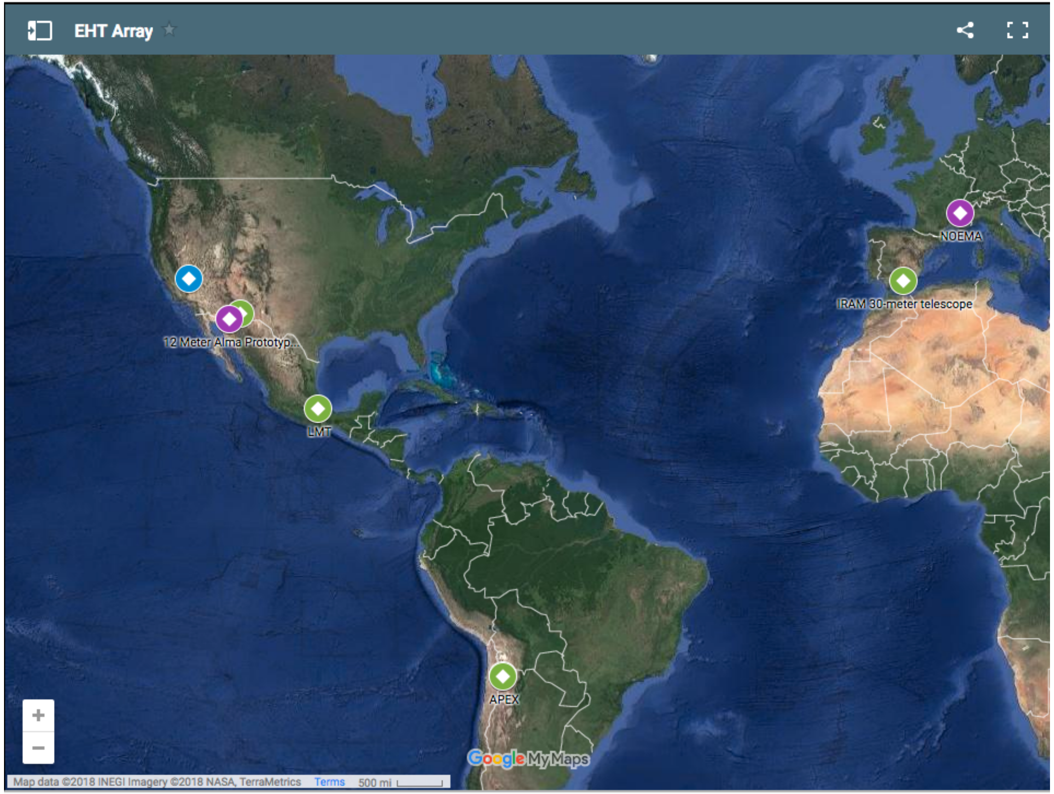


Credit: NASA/ESA/Hubble Heritage Team (STScI/AURA)/P. Cote (Herzberg Institute of Astrophysics)/E. Baltz (Stanford University)]; Event Horizon Telescope collaboration et al.

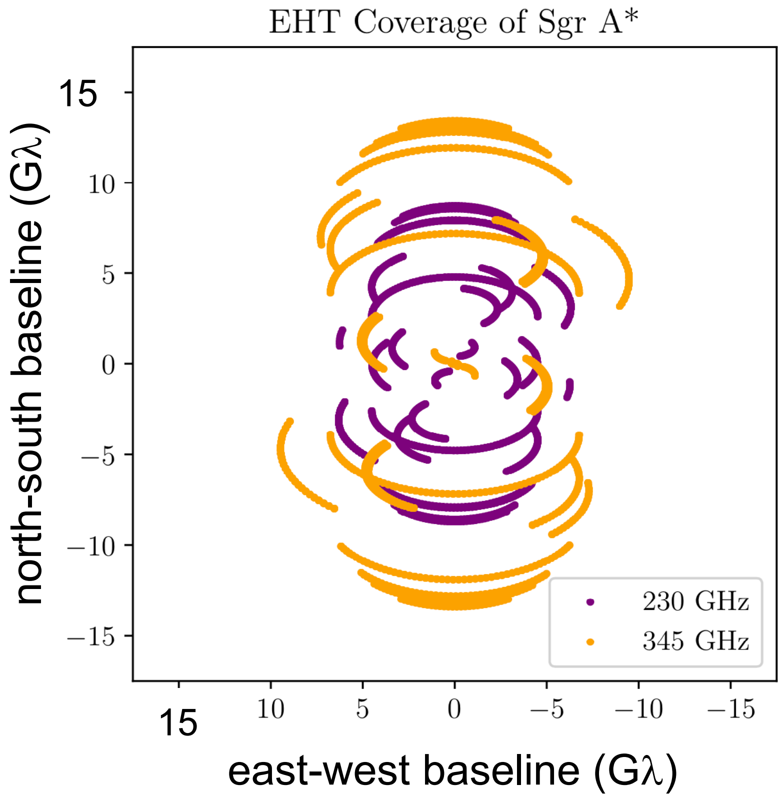
Black Hole Event Horizon Imaging

Space-based Interferometry

Nominal Event Horizon Telescope is extremely sparse array



Black Hole Event Horizon Imaging



Palumbo et al.

EHT is sparse array

- Many ”holes” in synthetic aperture

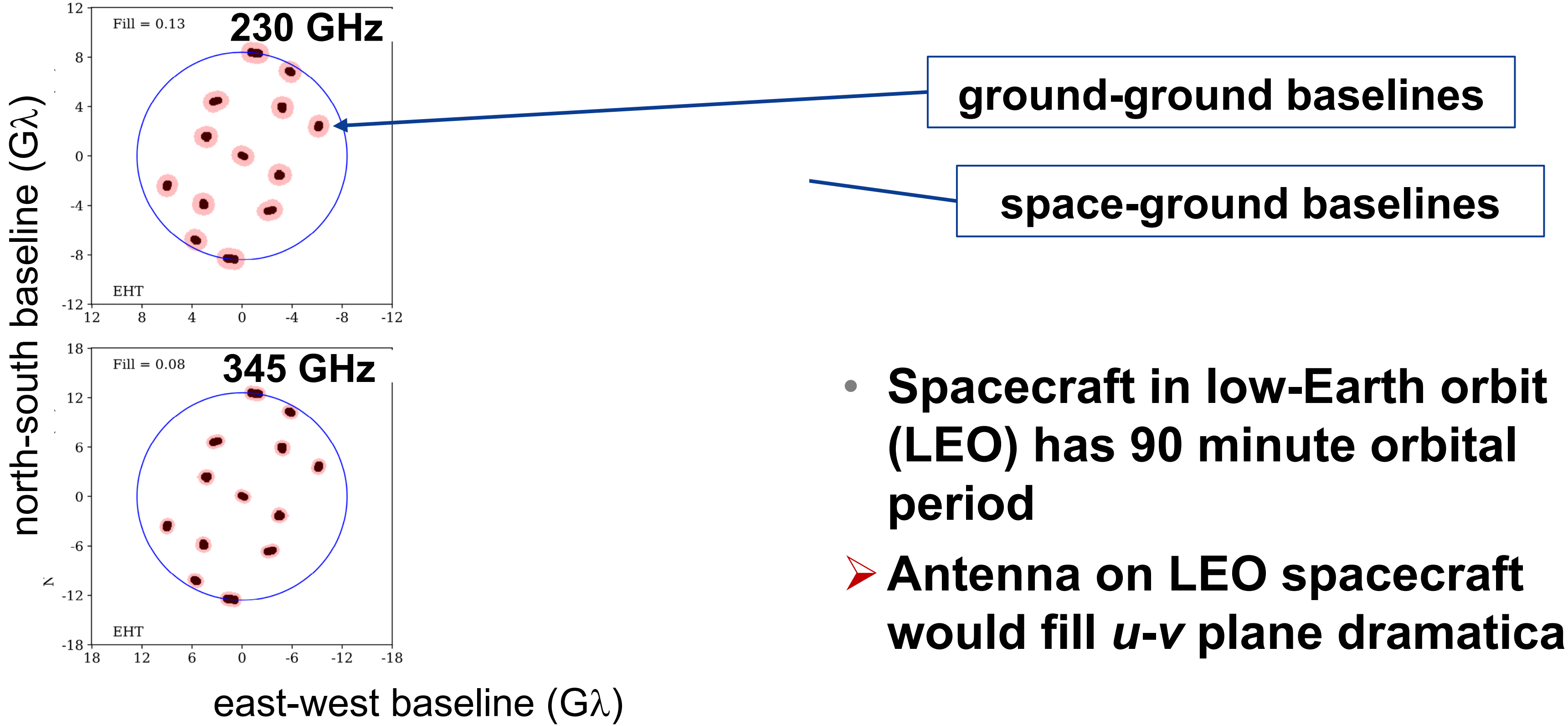
  … or many holes in *u-v* plane or Fourier plane

- Earth-rotation synthesis

  1 rotation = 24 hr

➢ Any way to fill these u-v plane holes?

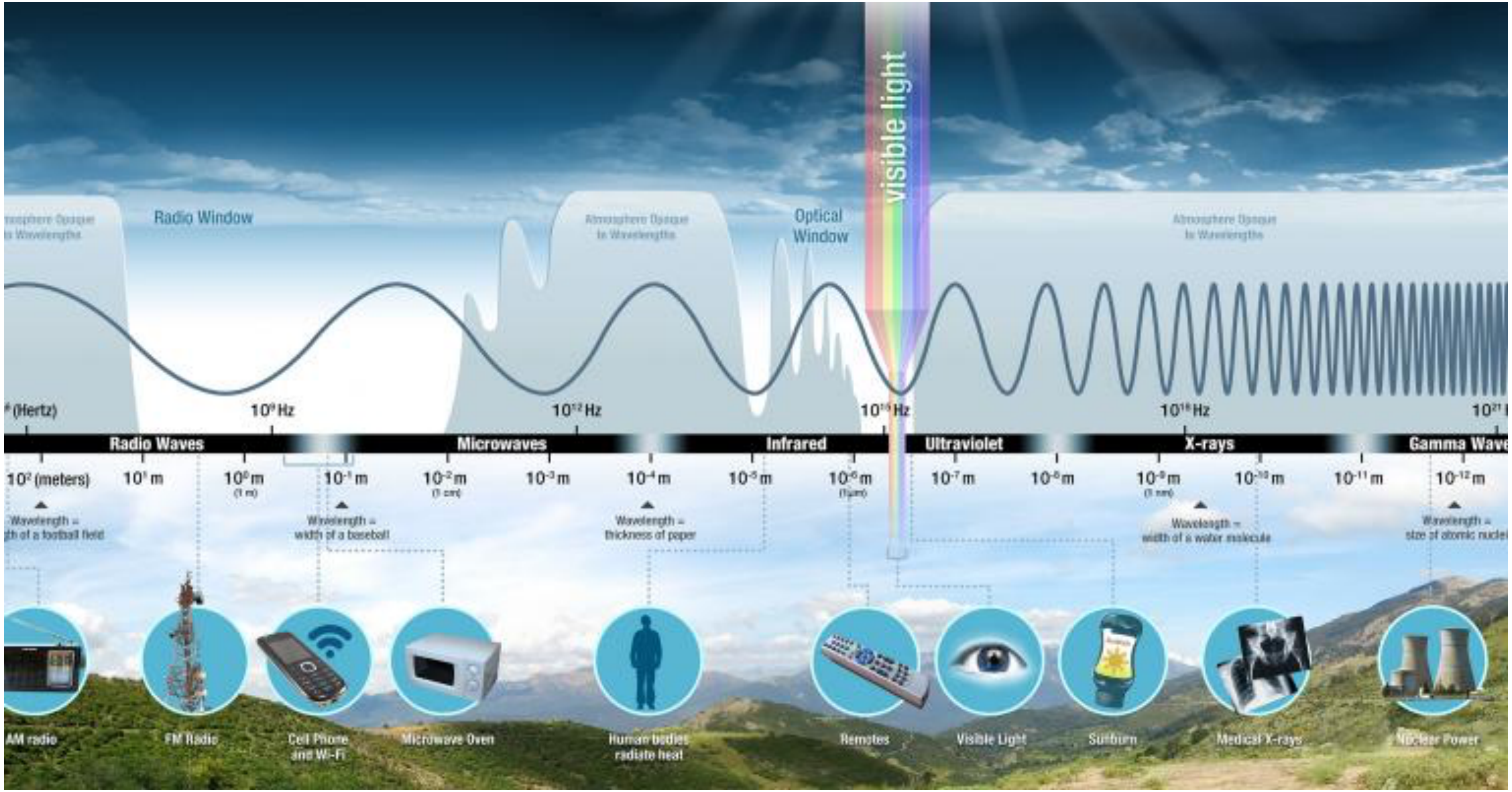
Black Hole Event Horizon Imaging



- Spacecraft in low-Earth orbit (LEO) has 90 minute orbital period
  - ➢ Antenna on LEO spacecraft would fill *u-v* plane dramatically!

Palumbo et al.

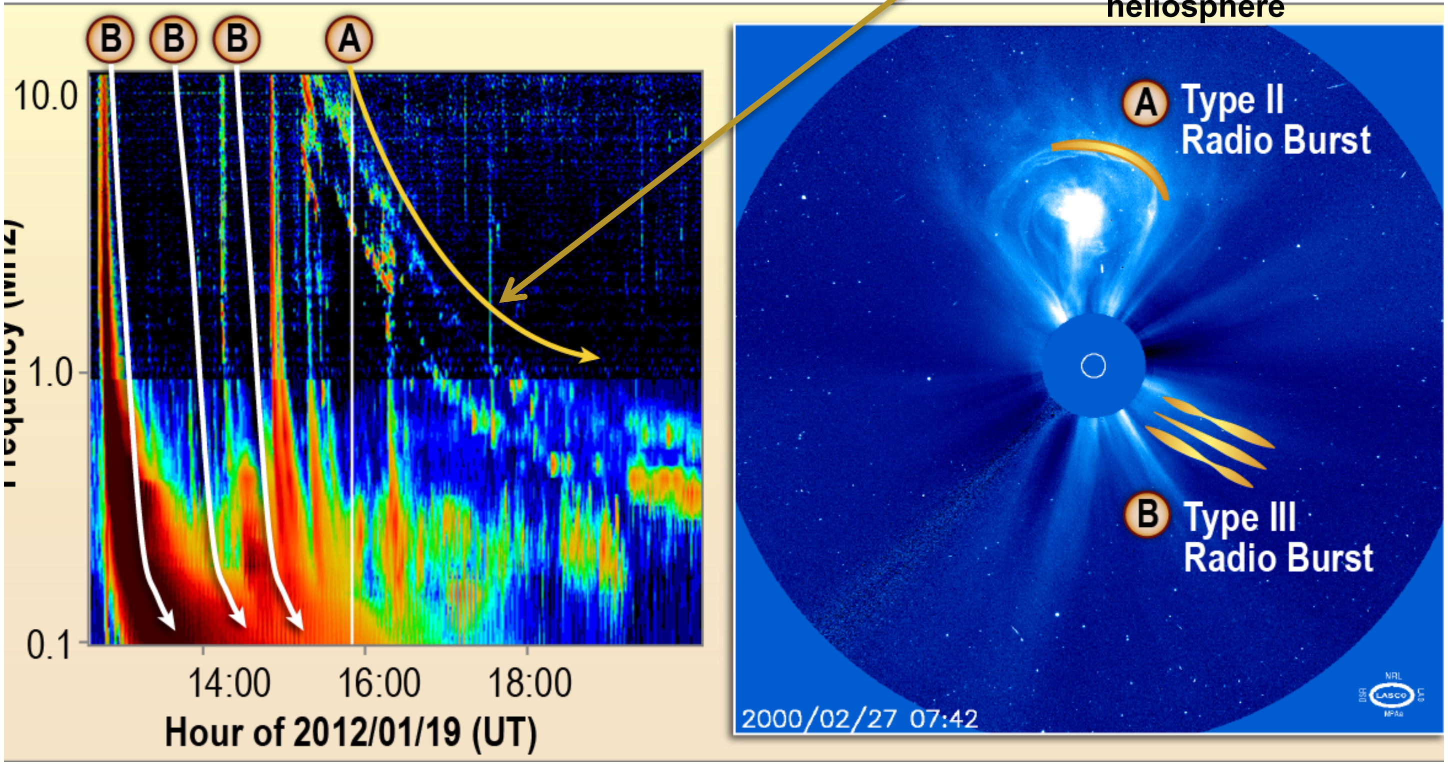
Electromagnetic Spectrum



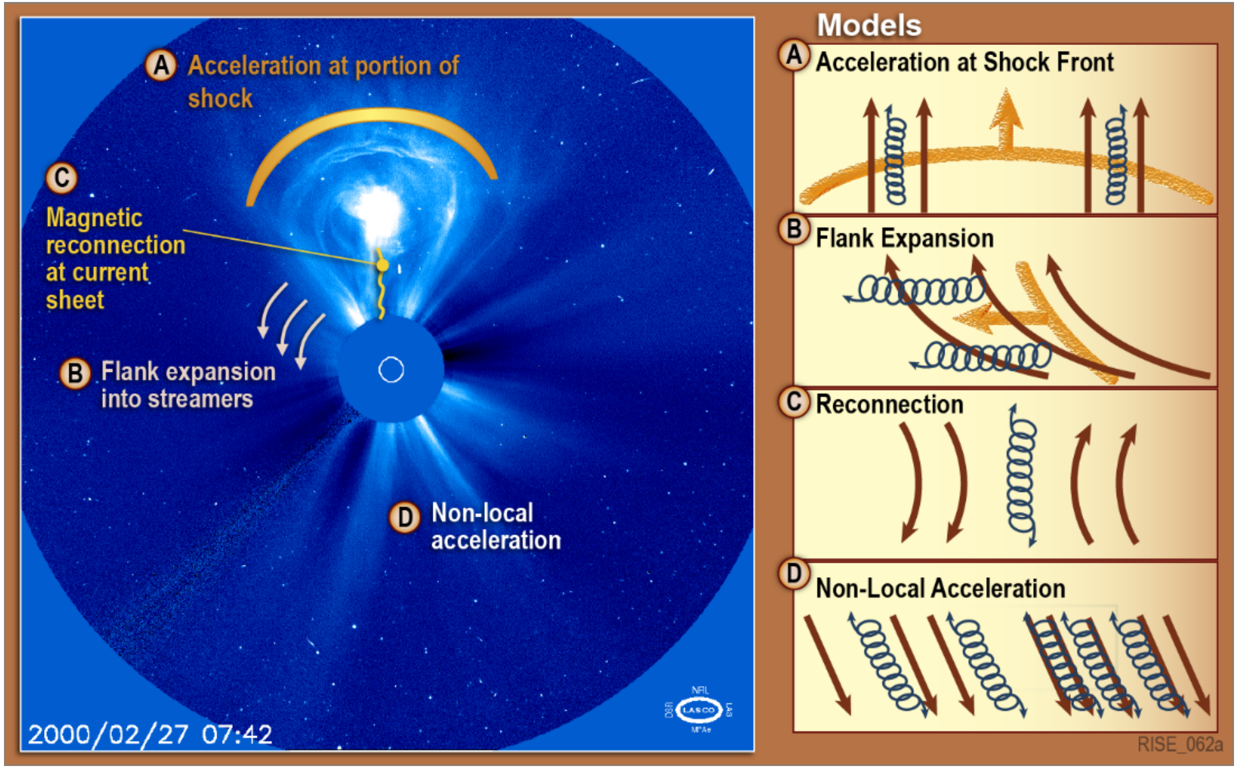
Solar Radio Bursts

Type II and III

Slowly descending in frequency as coronal mass ejections expand into heliosphere



Classes of Models for Ion and Electron Acceleration by CMEs

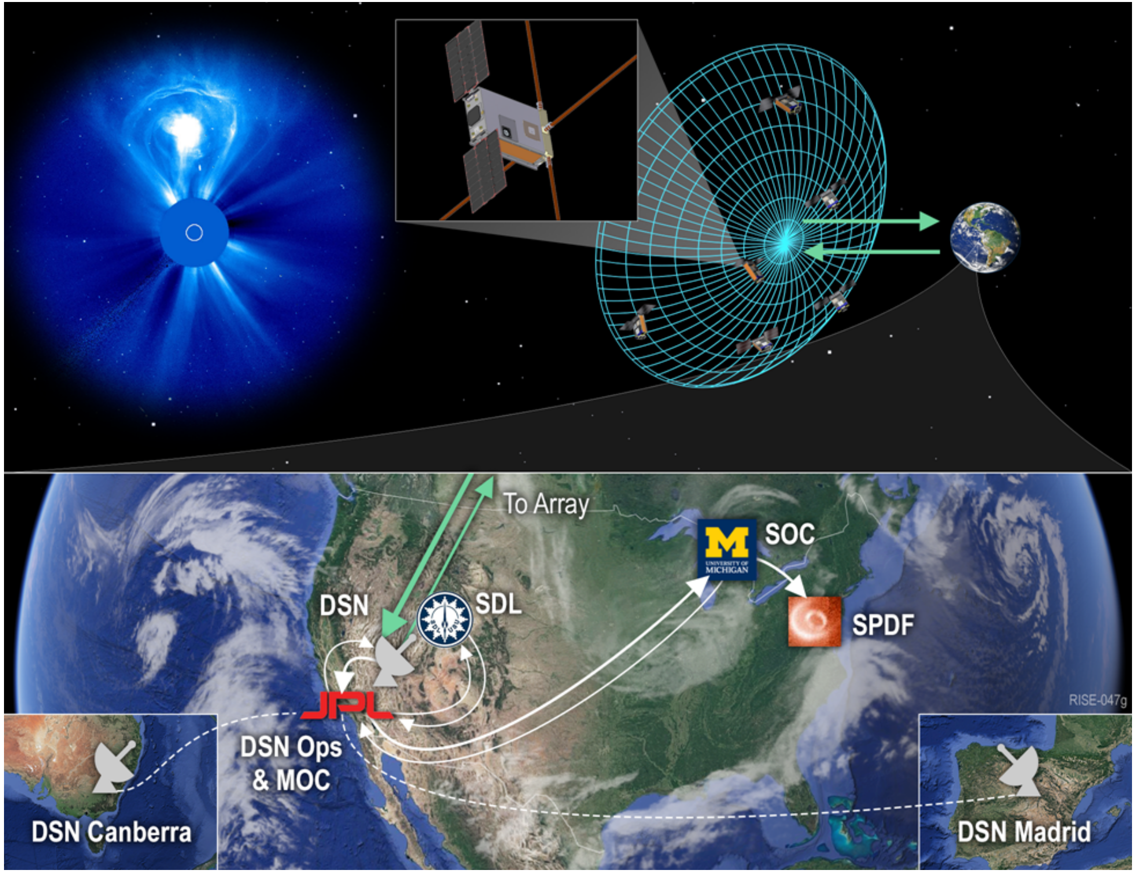


(A) Shock and compression acceleration in front of CME as it expands into corona

(B) Shock and compression acceleration on flanks as CME expands laterally into quiet streamers

(C) Magnetic reconnection at current sheets behind the ejecta

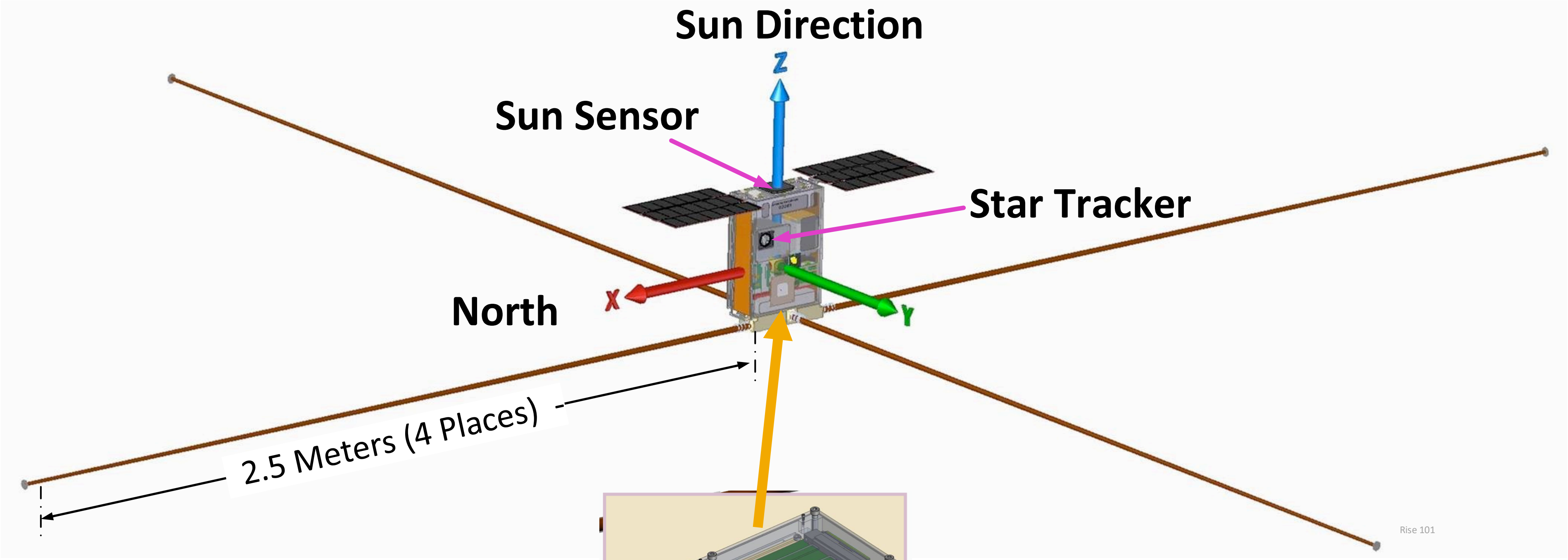
(D) Non-local acceleration as plasma is diverted and compressed by expanding filament

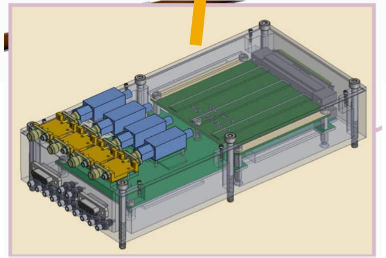


SunRISE

- First full interferometer in space, first decametric-hectometric (DH) imaging
- Loose formation of six 6U form factor smallsats in approximate 10 km sphere
- GEO Plus Orbit (25 hr orbit period)
- Radio receiver (0.1 MHz – 20 MHz) with crossed 5 m dipole antennas
- Relative position knowledge to within 3 m, timing to nanoseconds
- ➢ Need access to space because Earth's ionosphere is opaque!
- ➢ If selected, notional launch in 2023

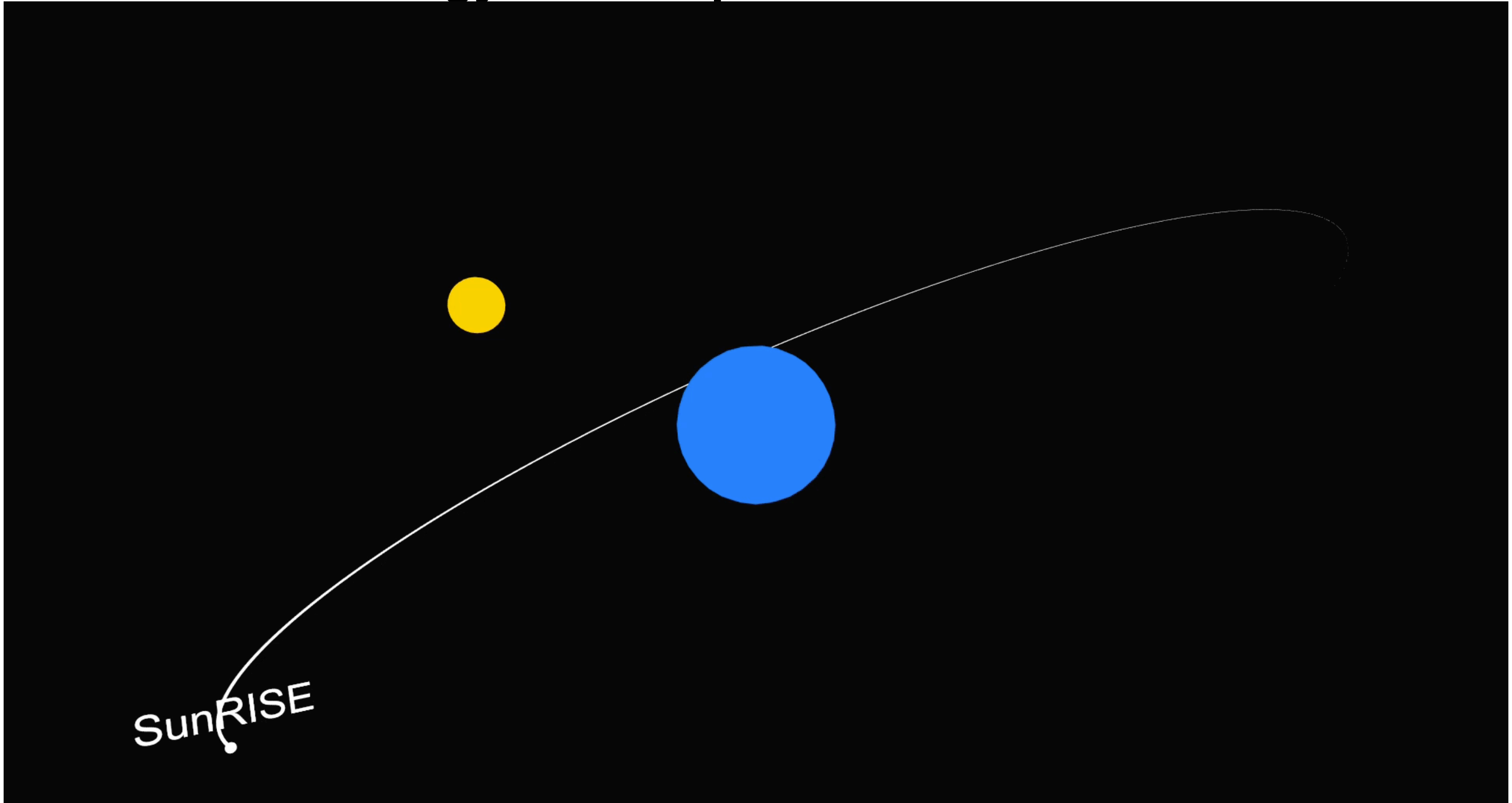
SunRISE Spacecraft and Science Instrument



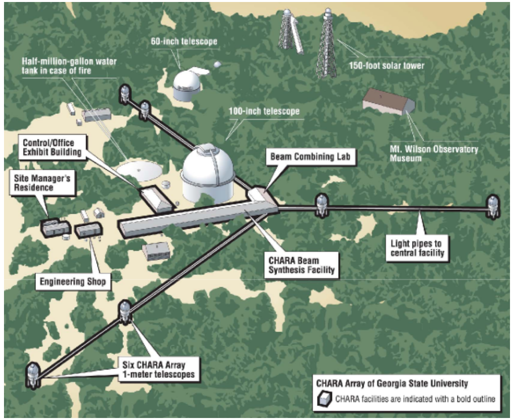


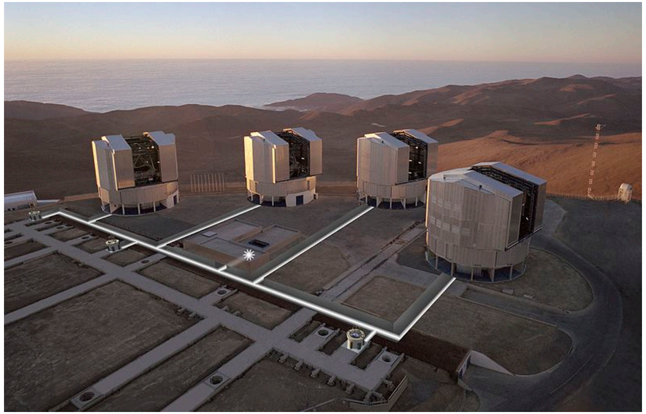
decametric-hectrometric radio receiver

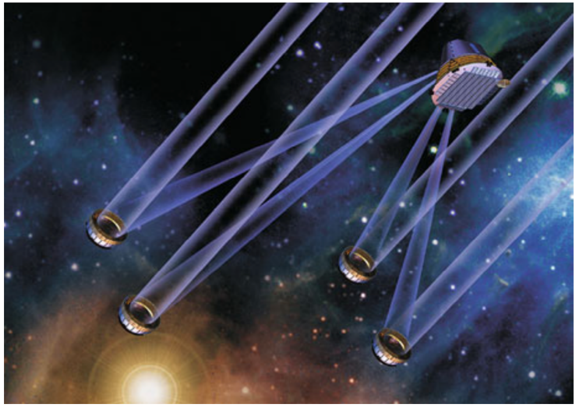
SunRISE Orbitology and *u-v* plane

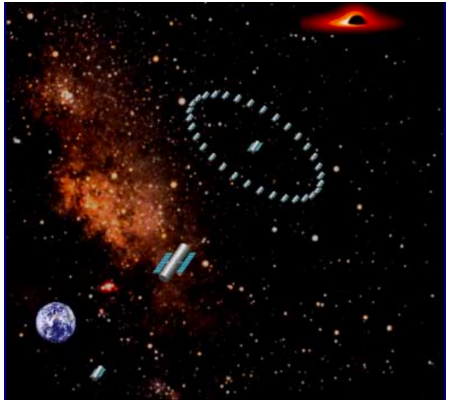


Beyond the Radio





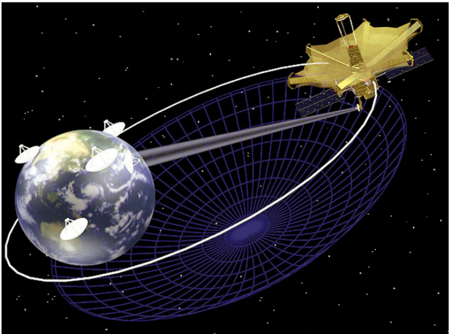


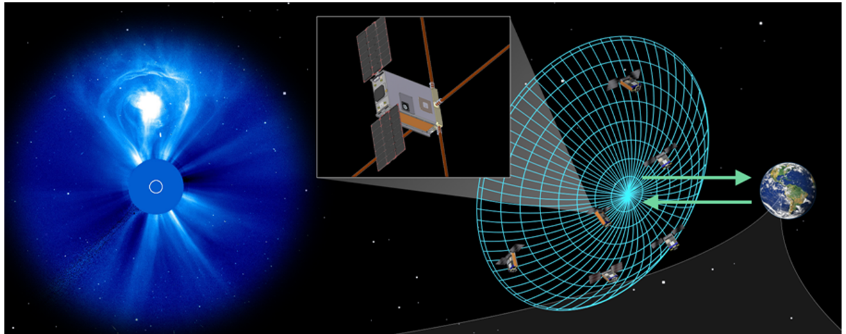


Credit: Georgia State Univ.; U.S. Naval Observatory; European Southern Observatory; Defrère et al.; W. Cash et al.

Summary

- High angular resolution imaging demands large apertures
- Interferometry is powerful (only) way to synthesize large apertures
  - Depends on relative antenna separations, knowledge not control
- Exciting future space possibilities for opening new windows, peering at black holes in new ways





Jet Propulsion Laboratory
California Institute of Technology

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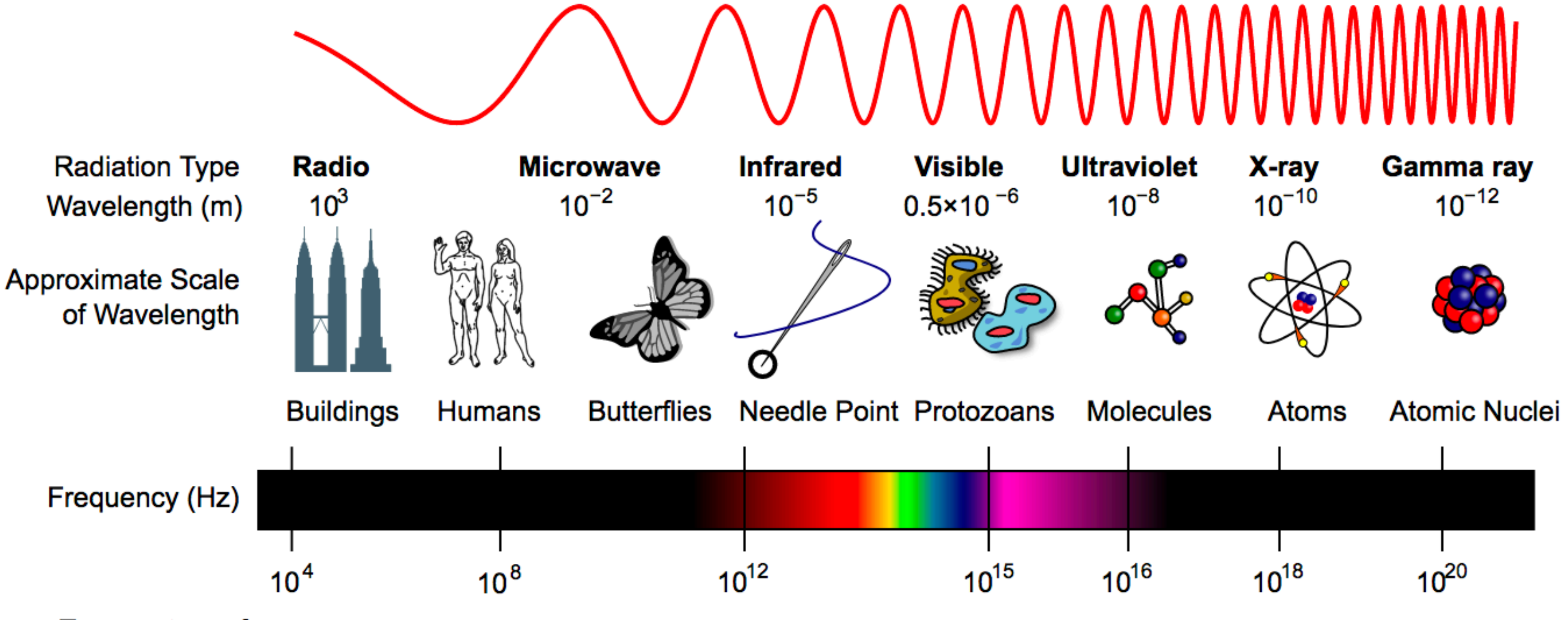
Electromagnetic Spectrum



Credit:
Wikipedia Images